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Report to Congressional Addressees

April 2026

TECHNOLOGY ASSESSMENT

Hydrogen Energy

Technologies Offer Potential Benefits but Face Challenges to Widespread Use

Accessible Version

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The cover image displays a stylized representation of hydrogen atoms and select uses of hydrogen energy.

Cover source: GAO (graphic elements), NASA/Bill Ingalls (Artemis II), Aapsky (bus)/Rawpixel (ship)/Alexlmx (forklift)/Imageflow (tank)/Iryna Petrenko (molecule)/stock.adobe.com | GAO-26-107932

TECHNOLOGY ASSESSMENT

Highlights of GAO-26-107932, a report to congressional addressees

April 2026

Hydrogen Energy

Technologies Offer Potential Benefits but Face Challenges to Widespread Use

Why GAO did this study

Hydrogen is a versatile chemical with many potential uses, including vehicle fuel cells, aviation fuel, and power generation. For decades, interest in hydrogen energy technologies to augment or replace diesel, natural gas, and electricity has garnered billions of dollars in research and development. The U.S. could produce hydrogen in vast quantities from domestically abundant resources. However, hydrogen energy is generally more costly than alternatives and infrastructure is lacking, so whether it will replace incumbent technologies is unclear.

This report examines: (1) current and emerging technologies for hydrogen production, transport, storage, and use; (2) potential benefits and challenges to developing or using these technologies; and (3) possible policy options.

To conduct this technology assessment, GAO searched the relevant literature; reviewed documents and reports; interviewed stakeholders from government, industry, academia, and nonprofits; conducted site visits; attended a conference; and convened a 3-day meeting of 18 experts from government agencies, industry, academia, and federally funded research and development centers. GAO is identifying policy options in this report (see next page).

View GAO-26-107932. For more information, contact Karen L. Howard, PhD, at HowardK@gao.gov.

What GAO found

Hydrogen energy technologies offer long-duration energy storage, increased transportation efficiencies, quiet operation, reduced air polluting emissions, and potentially broad availability. For example, hydrogen fuel cell power generation technologies could provide quiet, clean backup power to data centers and other large-scale operations during power outages. These generation technologies could increase overall electricity grid security by providing long-duration energy storage. Currently, hydrogen fuel cells provide about 0.03 percent of utility-scale electricity generation.

Current and potential hydrogen energy technologies

Source: Macrovector/stock.adobe.com (images). | GAO-26-107932

However, hydrogen energy technologies have not been widely adopted because of hydrogen's relatively high cost and limited market. Additionally, GAO identified four technical challenges to widespread use:

- **Efficiency and safety.** Hydrogen's physical characteristics make it particulary susceptible to efficiency losses, leakage, and emergency response risks.
- **Infrastructure.** Transport and storage infrastructure is generally lacking or confined to certain regions of the U.S., and existing natural gas pipeline infrastructure might not be suitable for hydrogen.
- **Geography.** Geographic constraints can increase transport and storage costs for hydrogen users.
- **Regulation and permitting.** Unclear federal jurisdiction and lack of standards can slow down projects.

Since the 1950s, the U.S. has made periodic investments in hydrogen as a potential power source and transportation fuel. Relevant past legislation cited goals such as energy security and resilience, market competitiveness, and prioritizing use of lower-emission energy technologies. GAO offers seven options that policymakers could consider to advance these goals and address challenges to hydrogen energy use. GAO formulated these options for five policy goals, identified through a review of historical congressional legislation related to hydrogen energy. See tables 1–5 in this report for additional policy options and details.

Policy Goals and Policy Options for Hydrogen Energy Technologies

Policy options	Opportunities / Considerations
Policy goal: Energy security and resilience.	
Policy options (report p. 22) • Identify energy system vulnerabilities and deploy solutions • Identify and address infrastructure needs • Develop or clarify regulations, standards, and oversight purview • Support research and development (R&D)	**Opportunities** • Could diversify the energy system and improve its resiliency. • Could make hydrogen more readily available as a tool to build resilience by producing energy independent of existing electricity grid infrastructure. **Considerations** • May reduce staff and financial resources for more cost effective or mature energy technologies that may provide similar benefits.
Policy goal: U.S. hydrogen market competitiveness.	
Policy options (report p. 23) • Implement market-stimulating mechanisms • Develop or clarify regulations, standards, and oversight purview • Support R&D • Evaluate hydrogen energy deployment and utility	**Opportunities** • Could help bridge the gap between the higher cost of hydrogen and the price customers are willing to pay. **Considerations** • There may not be sufficient or available transport and storage methods to support increased supply and demand.
Policy goal: Low-carbon energy transition.	
Policy options (report p. 25) • Implement market-stimulating mechanisms • Identify and address infrastructure needs • Develop or clarify regulations, standards, and oversight purview • Support R&D • Evaluate hydrogen energy deployment and utility • Support collaboration and consortia	**Opportunities** • Could help bridge the gap between the higher cost of low carbon hydrogen and the price customers are willing to pay. • Could reduce supply chain infrastructure limitations. • Could help identify whether, where, and when to use specific technologies. **Considerations** • May reduce staff and financial resources for other policy goals. • Resource- or time-intensive regulations or permitting requirements could hinder adoption of hydrogen energy technologies.
Policy goal: Prioritize technologies with near-term potential.	
Policy options (report p. 28) • Implement market-stimulating mechanisms • Support R&D • Evaluate hydrogen energy deployment and utility	**Opportunities** • Could streamline R&D for technologies on the cusp of commercialization **Considerations** • The most mature technologies may not be competitive in global markets or may not have many utilization opportunities.
Policy goal: Research, development, and innovation.	
Policy options (report p. 29) • Support R&D • Evaluate hydrogen deployment and utility • Support collaboration and consortia	**Opportunities** • Could enable scientific and technological developments and advancements for hydrogen energy and the larger scientific community. **Considerations** • There is no guarantee that additional R&D will result in technology deployment.

Source: GAO. | GAO-26-107932

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Abbreviations

DOE	Department of Energy
DOT	Department of Transportation
FCEV	fuel cell electric vehicle
FERC	Federal Energy Regulatory Commission
NASA	National Aeronautics and Space Administration
PHMSA	Pipeline and Hazardous Materials Safety Administration
R&D	research and development
USGS	U.S. Geological Survey

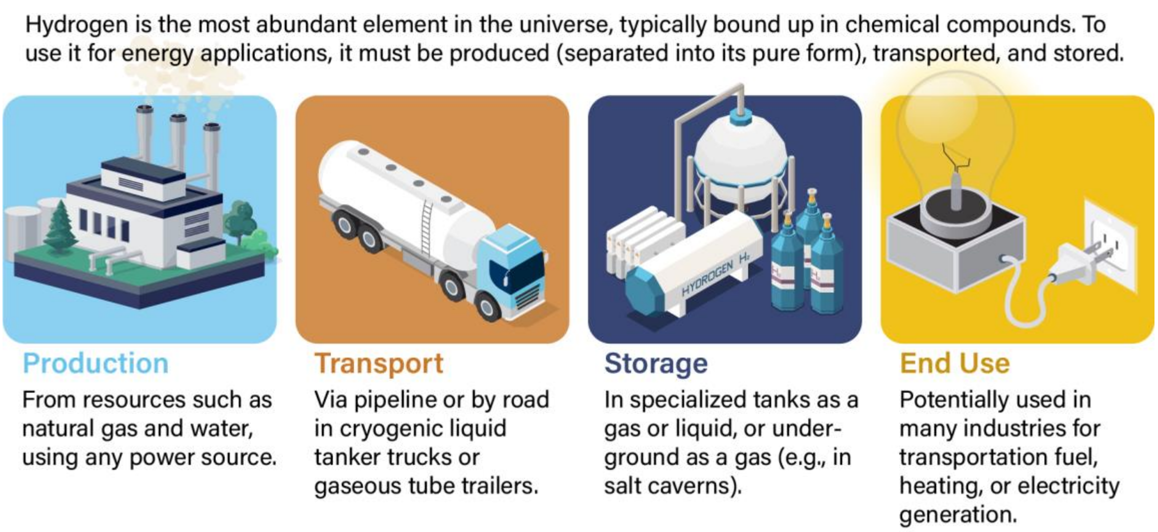
April 30, 2026

Congressional Addressees:

Hydrogen energy has the potential to augment or replace diesel, natural gas, and batteries in several applications. The federal government has invested billions of dollars in research and development (R&D), and some hydrogen energy technologies have matured to commercialization. For example, hydrogen is a preferred fuel for rockets because of its energy content by weight, and it is common in indoor forklifts because it produces no harmful, on-site air emissions other than water vapor and warm air. Future use at larger scales could improve electricity grid resilience and energy security, and hydrogen may offer advantages by reducing carbon emissions from heavy industry and heavy-duty transportation. However, hydrogen energy is generally more costly than the alternatives, and wide-scale infrastructure for hydrogen transport and storage is lacking. In general, it remains unclear whether hydrogen energy technologies will replace incumbent technologies in some sectors on a large scale or over what time frame.

This report examines the use of hydrogen energy technologies across four major steps in the supply chain—production, transport, storage, and end use (see fig. 1).

Figure 1: Four steps in the hydrogen energy supply chain



Source: GAO analysis of government reports (data); Petrovarga (production)/chakawut (transport)/macrovector (storage and end use)/stock.adobe.com (images). | GAO-26-107932

We prepared this report at the initiative of the Comptroller General. This report examines: (1) current and emerging technologies for hydrogen energy production, transport, storage, and use; (2) potential benefits and challenges to developing or using these technologies; and (3) policy options, or actions, to support a range of policy goals.

To address these objectives, we conducted a literature search; interviewed stakeholders from government, industry, academia, and nonprofits; convened a 3-day expert meeting; and conducted site visits in the Denver and San Francisco Bay areas. See appendix I for the full objectives, scope, and methodology used in this report, and appendix II for the list of expert meeting participants.

We conducted our work from November 2024 through April 2026 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analyses conducted, provide a reasonable basis for the findings and conclusions in this product.

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1 Background

1.1 Hydrogen

Hydrogen is the most abundant element in the universe.[1] It occurs naturally on Earth, most commonly bonded to other elements to form chemical compounds such as water (H_2O) and methane (CH_4). Different chemical processes can extract hydrogen from compounds for use in a variety of industries.

Hydrogen's unique physical and chemical properties make it well-suited for a wide range of end uses but also pose engineering- and infrastructure-related difficulties. It has the highest energy content per weight of any chemical fuel—with nearly three times the energy content per weight of gasoline—making it attractive for applications where weight is critical, such as rocket fuel. Hydrogen also burns hotter than other conventional fuels, which may make it ideal for high-heat industrial processes such as cement and steel manufacturing. However, hydrogen's small molecular size enables it to leak from containers more readily than most other gases and embrittle metal infrastructure used to store and transport it (see app. III for more information on embrittlement).

1.2 Hydrogen as an energy carrier

Energy from fossil fuels, nuclear power, or renewable power (e.g., solar, wind) can be used to extract hydrogen from a variety of resources such as water and natural gas. The initial sources of energy are considered "primary" energy sources because they are in their original or unaltered form. Hydrogen for energy use must first be converted to a usable form and is considered a "secondary" energy source, or "energy carrier."[2] As an energy carrier, hydrogen can be used to store, move, and deliver energy for heating, transportation fuel, and backup or emergency power. While hydrogen is a highly efficient energy carrier when used in fuel cells—two to three times more efficient than an internal

Hydrogen in Space Exploration

Since its creation, the National Aeronautics and Space Administration (NASA) has been instrumental to the research, development, and deployment of hydrogen energy technologies. Hydrogen fuel cells developed by NASA powered inhabited spacecraft during the Gemini, Apollo, and Space Shuttle programs and remain a critical technology for space operations. Also, liquid hydrogen fueled NASA's upper stage rockets for launching the Apollo missions to the moon, the Space Shuttle program, key launch vehicles used for high priority missions, and for the current Space Launch System which is returning humans to the moon.

NASA continues to pursue hydrogen energy research and development for aeronautics and space applications. For example, it is researching new thermal insulation systems for hydrogen storage to support future space exploration missions. According to agency officials and documents, any sustained human presence and economic activity on the moon will rely on hydrogen energy, because, unlike other sources, it could be produced on site from lunar ice.

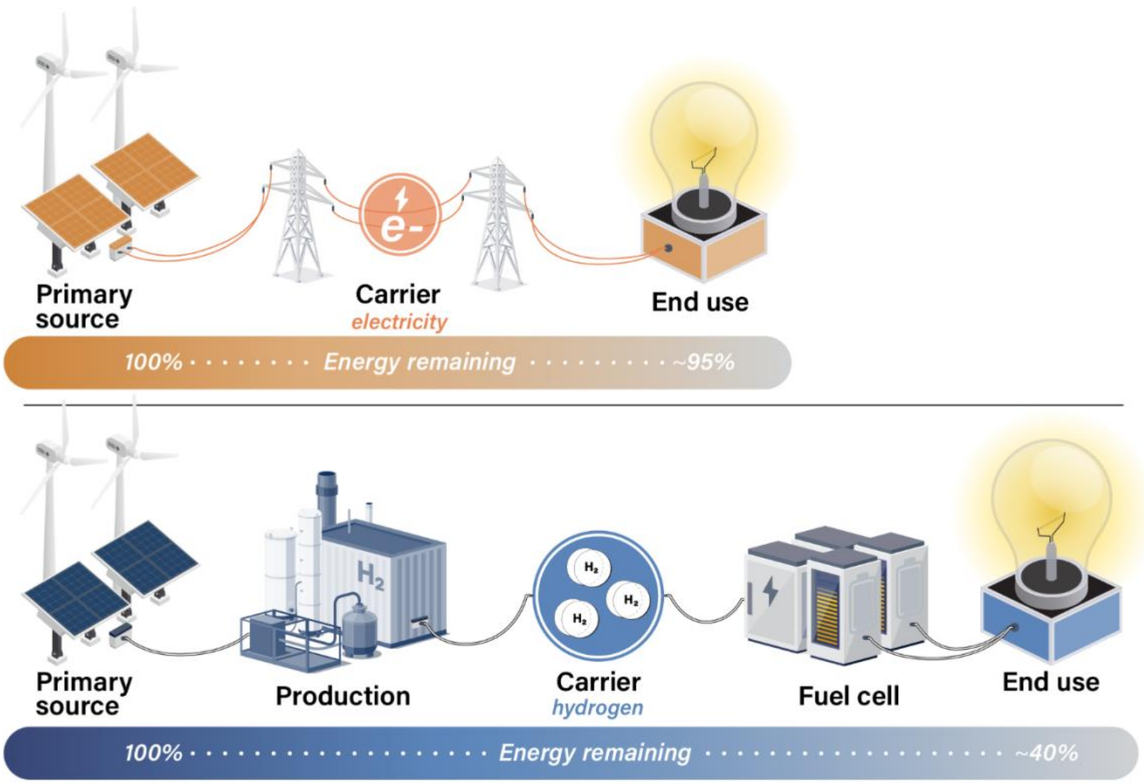
Source: GAO summary of information from NASA. | GAO-26-107932

[1]Pure hydrogen, also known as dihydrogen, typically exists on Earth as a molecule consisting of two hydrogen atoms joined by a single chemical bond.

[2]While hydrogen can exist naturally in its usable state—as a molecule of two bonded hydrogen atoms—the most accessible sources of hydrogen are larger chemical compounds that contain it.

combustion engine running on gasoline—producing hydrogen requires more energy than it provides when converted into electricity. The processes necessary to make hydrogen usable for energy—compression, liquefaction, or chemical conversion—also require externally supplied energy, resulting in overall efficiency losses (see fig. 2).

Figure 2: Total energy losses for selected energy carriers



Source: GAO analysis of government reports (data); GAO (graphic elements); Macrovector (primary source and end use)/Petrovarga (production, electricity carrier, and storage)/stock.adobe.com (images). | GAO-26-107932

Note: Energy remaining percentages reflect averages for transmission of electricity and electrolysis-based production, storage, and use of hydrogen in a fuel cell using renewable energy as a primary energy source.

2 Current Uses and Costs

2.1 Current use in the U.S.

The U.S. produces about 10 million metric tons of hydrogen per year, but the use of hydrogen for supplying energy is minimal.[3] For example, hydrogen fuel cells—one of the most commercially used technologies that supports hydrogen use for energy—provide about 0.03 percent of domestic utility-scale electricity generation capacity. Vehicles that use hydrogen fuel cells make up less than 0.01 percent of fuel consumption for light-duty and some heavy-duty vehicles (see app. IV for more information about fuel cells).[4] Nearly 90 percent of hydrogen produced in the U.S. is used in fossil fuel refining and ammonia production for agricultural use and manufacturing processes.

2.2 Current cost and market dynamics

The purchase price of hydrogen varies depending on the production method (see 3.1). It also depends on logistical considerations such as the volume of hydrogen needed, the transport distance between production and end use, and the end use industry–for example, within the manufacturing sector, the average price of hydrogen varies among the different subsectors (see fig. 3).

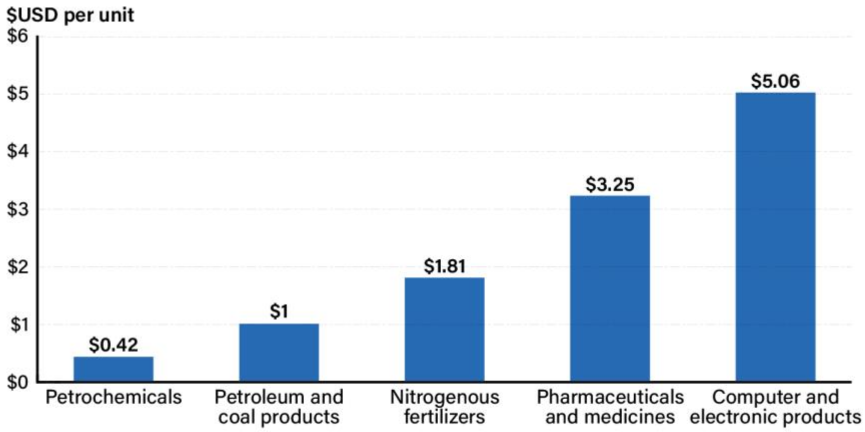
In certain sectors, such as transportation, hydrogen can be much more costly than alternatives (see fig. 4). For example, in some cases, hydrogen transport and storage needs can roughly double the cost to the end-user. We previously reported on the cost of hydrogen restricting its use for energy purposes.[5]

[3]This amount is roughly equivalent to the energy content of 10 billion gallons of gasoline, the amount the U.S. transportation sector uses in an average month.

[4]These data come from the U.S. Energy Information Administration for utility-scale electricity generation (February 2025) and from the Department of Transportation (June 2024) for fuel cell vehicles. In a fuel cell, hydrogen chemically reacts with oxygen to produce electricity, heat, and water without other harmful emissions at the point of use, with higher efficiency than combustion engines that use traditional fuels.

[5]For example, we reported on the cost of hydrogen energy in 1979, 1980, 2008, and 2024: GAO, The Potential For Hydrogen As an Energy Source, EMD-79-58 (Washington, D.C.: Apr. 1979); GAO, Views on the proposed "Hydrogen Fuel Development and Use Act of 1979," EMD-80-B3 (Washington, D.C.: Feb. 21, 1980); GAO, Hydrogen Fuel Initiative: DOE Has Made Important Progress and Involved Stakeholders but Needs to Update What It Expects to Achieve by Its 2015 Target, GAO-08-305 (Washington, D.C.: Jan. 2008) ; GAO, Science & Tech Spotlight: Hydrogen Uses, GAO-24-107489 (Washington, D.C.: May 2024).

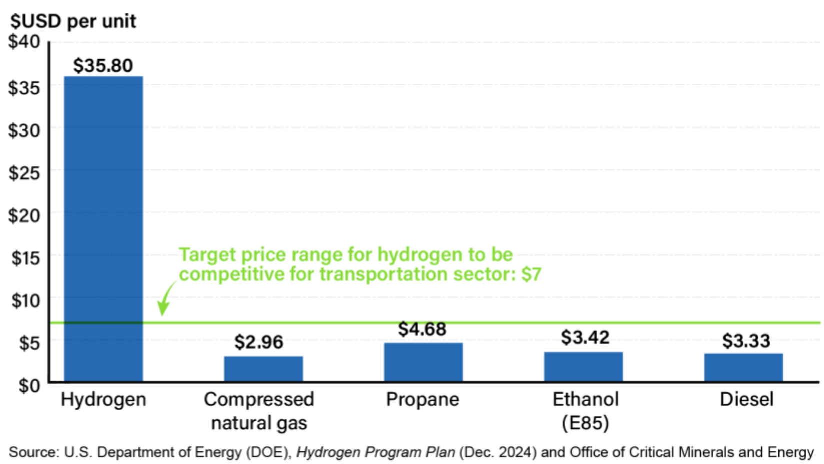
Figure 3: National average purchase price for hydrogen by selected manufacturing subsector on an energy-equivalent basis, 2022



Source: U.S. Energy Information Administration (EIA), *Manufacturing Energy Consumption Survey* (2022) (data); GAO (graph). | GAO-26-107932

Note: Prices adjusted on a per unit basis. The unit is the amount of hydrogen required to equal the energy content of one gallon of gasoline. The figure reports national average end use purchase price for hydrogen across manufacturers within each subsector, and does not consider differences in location, hydrogen production path, or various business practices and delivery arrangements for each manufacturing subsector that can impact the price of hydrogen. Petrochemicals are chemical products derived from crude oil and natural gas such as ethylene and benzene; petroleum and coal products are materials and fuels produced by refining crude oil or processing coal such as gasoline and asphalt.

Figure 4: Summary of national average retail fuel prices on an energy-equivalent basis, October 2025



Source: U.S. Department of Energy (DOE), *Hydrogen Program Plan* (Dec. 2024) and Office of Critical Minerals and Energy Innovation, *Clean Cities and Communities Alternative Fuel Price Report* (Oct. 2025) (data); GAO (graph). | GAO-26-107932

Note: Prices adjusted on a per unit basis. The unit is the amount of fuel required to equal the energy content of one gallon of gasoline. The price data for hydrogen are primarily derived from light duty vehicle retail stations, most of which are located in California, and is based on a very small sample of hydrogen price information. E85 is comprised of gasoline and ethanol that contains 51 – 83 percent ethanol, depending on location and season. For industrial processes using established onsite infrastructure, the price of hydrogen may be much lower than the retail price indicated in the graph—approximately $1.25 per unit.

Although hydrogen is widely used for chemical and industrial processes, there is a relatively limited market for its use for supplying energy whereas some fuels—natural gas, diesel, and others—have well-established markets and infrastructure. Hydrogen energy producers and consumers are often at an impasse: producers hesitate to scale up infrastructure without assured demand, discouraging users from choosing high-cost hydrogen without an established supply network. Some users, however, such as NASA, may be willing to pay higher prices for mission-critical needs that rely on specific hydrogen properties. But, without other requirements or incentives, cost-sensitive consumers may choose other options.

2.3 Potential cost and market developments

Ongoing efforts and developments across government and industry, as well as emerging global demand, could expand hydrogen use, address its comparatively high cost, and further diversify the energy system. The cost and use of hydrogen may continue to evolve in the future:

- **Cost reduction efforts.** The Department of Energy (DOE) launched an initiative to reduce the cost of low carbon hydrogen to $1 per kilogram by 2031.[6] The initiative includes R&D and analyses of various technologies.
- **Technology development.** Some technologies that support hydrogen for energy use are under development, but stakeholders suggest that their maturation could help reduce the cost of hydrogen across the supply chain. For example, extraction of hydrogen gas from naturally occurring geologic resources could offset hydrogen production costs.
- **Expanded industrial use.** Increased use of hydrogen in certain sectors could stimulate overall hydrogen demand, reduce costs, and lead to broader uptake of hydrogen energy technologies. For example, hydrogen is an essential feedstock in many chemicals and biofuels.
- **Global competition and export.** Global hydrogen demand increased about 2 percent per year since 2022, reaching approximately 100 million metric tons in 2024.[7] Hydrogen-related exports could include pure hydrogen, hydrogen derivatives (such as ammonia or as a component of sustainable aviation fuel), and hydrogen energy technologies (such as electrolyzers).
- **Diversify the U.S. energy system.** Technologies that support hydrogen use for energy offer opportunities to further diversify the U.S. energy system, which

[6]The Hydrogen Shot is one of eight goals launched under DOE's "Energy Earthshot Initiative." Hydrogen Shot launched in 2021 to reduce the cost of low-carbon hydrogen by 80 percent, to $1 per kilogram in 1 decade (by 2031). For the purposes of this report, low-carbon hydrogen is roughly equivalent to clean hydrogen. Clean hydrogen is hydrogen that is produced through a process that results in a life cycle greenhouse gas emissions rate of no more than 4 kilograms of carbon dioxide equivalent per kilogram of hydrogen, which generally aligns with the definition in what is commonly referred to as the Inflation Reduction Act of 2022. See An act to provide for reconciliation pursuant to title II of S. Con. Res. 14., Pub. L. No. 117-169, 136 Stat. 1818, 1937 (2022), codified at 26 U.S.C. § 45V(c)(2)(A).

[7]International Energy Agency, *Global Hydrogen Review 2025* (Sept. 2025).

can mitigate supply chain shocks. For instance, data centers are interested in deployment of fuel cells in the near-term due to supply chain constraints and long permitting processes.

3 Current and Potential Benefits

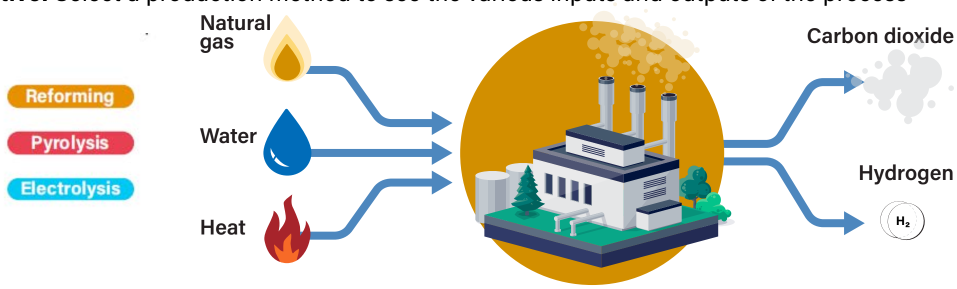
As an energy carrier, hydrogen offers potentially broad access, quiet operation, high efficiency at the point of use, the potential to improve power resiliency and stability, and reduced air polluting emissions. Currently, benefits of hydrogen energy technologies are limited due to their use in applications that consume smaller amounts of hydrogen, such as forklifts and generators for smaller-scale energy purposes. Other, large-scale potential applications include buses, trucks, microgrids, and energy storage.

3.1 Varied production inputs

Hydrogen can be produced through many methods and from a variety of feedstocks, which could make hydrogen available for a wide range of users and energy applications. This flexibility may also benefit users who prefer certain production pathways based on input cost or environmental impact (see fig. 5).

Figure 5: Inputs and outputs for selected hydrogen production pathways

Interactive: Select a production method to see the various inputs and outputs of the process



Source: GAO analysis of government reports (content); GAO (icons); Petrovarga (reforming and electrolysis)/Macrovector (pyrolosis)/ stock.adobe.com (images). | GAO-26-107932

Natural gas-based production

Hydrogen produced from natural gas accounts for about 95 percent of production in the U.S. Natural gas-based production methods leverage existing pipeline infrastructure and generally cost less than alternatives. These methods include:

- **Natural gas reforming,** which uses thermal processes to extract hydrogen from the methane in natural gas.

[8] Hydrogen energy has no harmful gaseous emissions at the point of use when used in a fuel cell. However, there is significant variability in emissions profiles between different hydrogen production technologies. Reducing air polluting emissions through the use of hydrogen is dependent on the hydrogen production methods. Emissions need to be assessed over the complete life cycle of a fuel's use including production, distribution, use, and disposal. When a fuel source is produced using electricity the emissions profile of the generation method must also be considered (e.g., solar, coal, wind, etc.). Hydrogen feedstocks can cause upstream emissions before production, such as when natural gas is produced. Midstream emissions may occur during hydrogen production but are unrelated to the production process (e.g., from leaky or inefficient equipment). Downstream emissions can occur after production, for example during transport or storage.

Examples include steam methane reforming, a heat-absorbing process that uses superheated steam, and autothermal reforming, a heat-producing process that burns methane in a low-oxygen environment. These methods create a range of emissions including carbon dioxide.[9]

- **Methane gas pyrolysis**, which uses heat to thermally decompose the methane in natural gas in the absence of oxygen, yielding hydrogen and solid carbon, without carbon dioxide emissions. This technology is expected to be cost-competitive due to the revenue associated with solid carbon. Solid carbon is used in tire manufacturing and can also be upgraded into higher value materials such as graphene, thereby displacing critical minerals like graphite.

Water-based production

Electrolysis uses electricity to extract hydrogen from water and does not create carbon dioxide or other emissions at the point of production. Water-based electrolysis production methods account for about 1 percent of hydrogen production in the U.S and generally cost more than natural gas-based methods due to electricity costs. These methods include:

- **Low-temperature electrolysis**, which splits water molecules to separate hydrogen from oxygen. This method is technologically mature and has established supply chains.

- **High-temperature electrolysis**, which splits the water molecules in superheated steam and separates hydrogen with solid ceramic barriers.[10] This method is less technologically mature but has higher electrical efficiency and the ability to recycle heat from external high-heat sources.

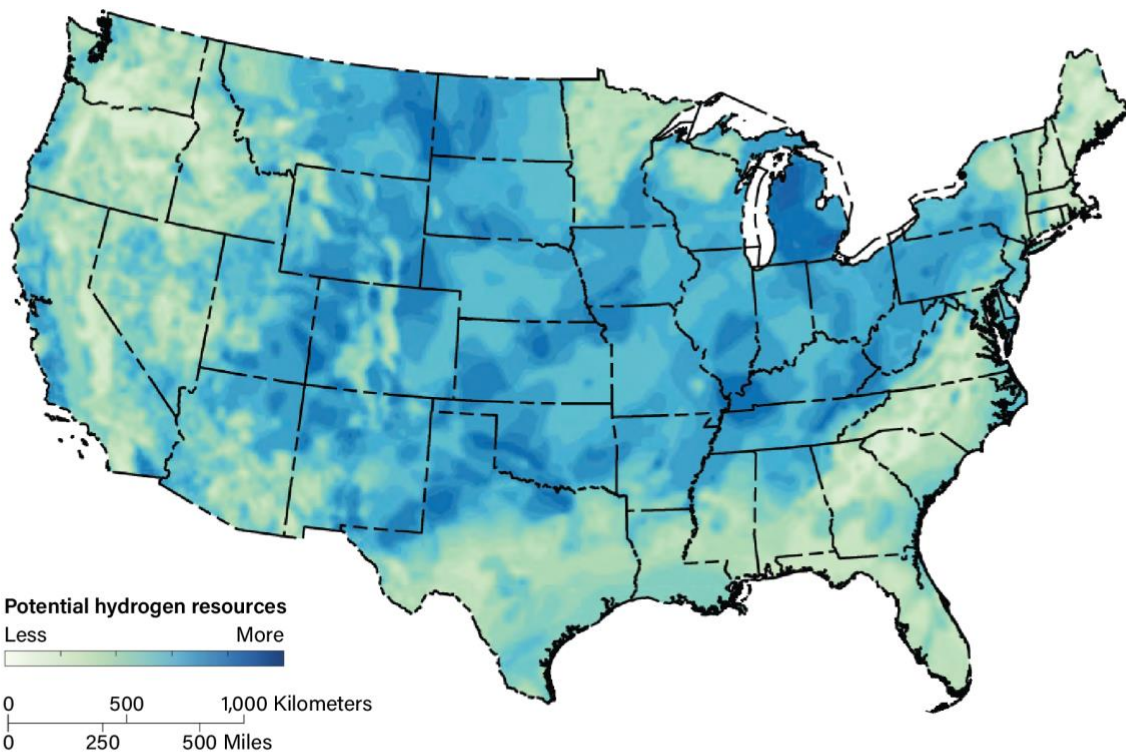
[9]Carbon capture, utilization, and storage (CCUS) technologies could be used to capture carbon dioxide before it is vented to the atmosphere. See, e.g., *Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage*, GAO-22-105274 (Washington, D.C.: Sept. 29, 2022).

[10]High-temperature electrolysis devices use materials such as rare earth elements in the ceramic internal barriers used to filter hydrogen and are dependent on limited global supply chains for critical minerals.

Future Production: Geologic Hydrogen

Geologic hydrogen extraction may offer new opportunities for low-cost, low-carbon production, and for repurposing oil and gas production technologies. Hydrogen gas forms naturally through interactions between groundwater and certain minerals and gets stored in certain layers of hard rock. These subsurface accumulations of natural hydrogen can be difficult to detect and extract. The U.S. Geological Survey (USGS) is working to identify U.S. regions most likely to contain hydrogen resources, with one study estimating that 2 percent of the global total could contain more energy than all proven natural gas reserves on Earth.

Potential accumulations of subsurface natural hydrogen resources in the contiguous United States



Source: GAO summary of information from U.S. Geological Survey (USGS) (text); USGS (map). | GAO-26-107932

3.2 Reduced noise, no on-site harmful emissions, and rapid refueling

For some applications, hydrogen offers important operational benefits. For example, hydrogen fuel cell-powered forklifts and generators have been commercialized because they operate quietly without harmful on-site air pollutant emissions and can be refueled more quickly than competing technologies.

Forklifts

Hydrogen fuel cell forklifts are a widely deployed hydrogen energy technology. They are beneficial in enclosed settings like warehouses and distribution centers because they do not emit harmful emissions that require expensive and complex ventilation systems to maintain safe environments for employees. They have more compact refueling stations and quicker refueling times-–about 3 minutes—than battery electric forklifts. They also operate much longer between refueling than batteries do between recharging, according to officials at the Department of Transportation. The benefits of rapid refueling are especially valuable for businesses that operate multiple shifts with no downtime to recharge equipment. As of 2023, more than 60,000 forklifts, or 16 percent of all forklifts used in the U.S., were powered by hydrogen.[11] By 2024, the number increased to more than 70,000 hydrogen forklifts.

Generators

Hydrogen fuel cell-powered generators could offer an alternative to diesel for cases that require low noise and air pollution, such as hospitals and construction sites. Stakeholders from one company we spoke with told us they leverage cryo-compressed hydrogen to provide services to customers, primarily in the form of onsite power generation. Customers for onsite power generation include data centers, whose power usage can impact available energy for the surrounding community. These stakeholders also told us that in Colorado, oil and gas companies are looking for alternatives to their drilling rigs that currently run on diesel generators, due to local concerns about smog and health impacts.

3.3 Better range, duration, and efficiency for some commercial vehicles

In 2024, the transportation sector was the largest contributor to CO_2 emissions in the U.S., accounting for over one-third of all emissions. Battery electric vehicles offer some environmental advantages over petroleum-based vehicles and have become a large part of the low-emissions light vehicle market. However, electric batteries are not well suited for heavy-duty vehicles over long distances, aircraft, or maritime vessels because they are heavy, have long-charging times, and have less energy content by weight, factors that are important in those sectors.

Heavy-duty vehicles

Hydrogen fuel cell buses and heavy-duty trucks offer enhanced performance, efficiency, and reduced emissions. They operate without air pollutant emissions and with a smoother ride and more powerful torque than diesel vehicles. Compared to electric vehicles, hydrogen vehicles have quicker refueling time and better range. Stakeholders from a transit agency we spoke with told us that their hydrogen fuel cell buses experience few weather-related efficiency issues, are less expensive to operate, and allowed them to expand their low-emission fleet.

[11] DOE supported the deployment of fuel cell forklifts including through funds from the American Recovery and Reinvestment Act of 2009 (ARRA), investing about $9.7 million with an industry cost share of $11.8 million for 713 fuel cell powered forklifts. Pub L. No 111-5, 123 Stat. 115 (2009). The market has continued to grow independently of DOE funding with less than 2 percent of deployed hydrogen forklifts supported by DOE as of 2022.

Light-Duty Hydrogen Vehicles

Light-duty hydrogen fuel cell electric vehicles (FCEV) have not achieved significant market acceptance despite interest and investment, in part due to limited infrastructure. Initially, adoption of FCEVs was fairly rapid. Globally, the number of light-duty FCEVs on the road increased from 2,000 in 2015 to 19,000 in 2019. Purchases peaked at 16,000 in 2021 but declined to 5,000 in 2024. By comparison, the number of battery electric vehicles on the road increased from 17,000 to 7.2 million between 2010 and 2019. Many regions lack access to hydrogen refueling stations, and the stations that are available can experience temporary closures, limited operating hours, or long wait times due to supply disruption and frequent equipment failures. These inconveniences, along with recent increases in hydrogen prices, have made light-duty FCEVs less competitive.

Source: GAO analysis of literature and government reports. | GAO-26-107932

Aviation

Aircraft fuel has been difficult to replace with low-carbon alternatives because electric batteries are too heavy, and sustainable aviation fuels are costly and in limited supply. Aircraft powered by hydrogen offer several advantages over conventional aircraft. They are more efficient because hydrogen fuel has more energy content per weight, allowing for extended range and novel missions not feasible with conventional fuels. Stakeholders from one company we spoke with told us that longer flight duration could be beneficial for wildfire detection and monitoring, data collection, weather modeling, and providing telecommunications to disrupted regions. Additionally, because of their relatively quiet operation and low heat and emission signatures, hydrogen fuel cell aircraft may be ideal for some military applications, according to experts. However, hydrogen requires more storage space than conventional aviation fuel and liquid hydrogen storage tanks have structural limitations that will require redesign of existing aircraft. Maintaining

Hydrogen Aircraft Design

While hydrogen provides more energy relative to weight than conventional fuels, it provides less energy by volume, so it requires more space. Additionally, hydrogen cannot be stored in the wings because its tanks are too bulky. Solutions range from placing the tank in the fuselage to complete redesigns that integrate hydrogen storage.

Source: GAO analysis of scientific literature and government reports (text); GAO (graphic elements); Golden sikorka (left and mid)/macrovector (right)/ stock.adobe.com | GAO–26–107932 cryogenic temperatures for liquid hydrogen and managing heat generated by fuel cells add additional considerations.

Maritime

Hydrogen-powered maritime vessels are quieter, more efficient, and release less liquid or atmospheric pollution than conventional diesel-powered maritime vessels. These benefits can help protect wildlife, increase sonar mapping accuracy, and enhance the experience of people operating or traveling on the vessels. Projects include a 75-passenger ferry that completed a 6-month demonstration project during 2024 in San Francisco, and a cruise line that has announced it has two hydrogen-powered cruise ships currently under construction.

3.4 Hydrogen energy provides power resilience and stability

The North American Electric Reliability Corporation and DOTestimate that higher energy demand and increasing reliance on intermittent renewables could result in supply shortfalls and increasing reliability issues.[12] Hydrogen can provide an option to diversify and improve the resiliency and stability of energy systems by providing local power independent from the larger electricity grid and capturing excess renewable energy production for later use to stabilize the grid.

Microgrid power

The rapid expansion of data centers and their reliance on diesel backup power have raised concerns about environmental and health effects. When coupled with hydrogen fuel cell technologies, microgrids can provide power for large-scale operations during power outages without the noise and harmful emissions of diesel power generation. Representatives from one company we spoke with have developed a hybrid battery and hydrogen microgrid system that can provide clean energy for at least 48 hours to a city in California that experiences frequent electricity loss.

Long-term storage and grid stabilization

Using hydrogen for longer-duration energy storage is an emerging effort that, according to stakeholders, can increase overall energy system security. For example, when electricity production exceeds demand, hydrogen can be produced using excess energy, then stored for use when demand exceeds supply. Hydrogen energy storage can be particularly helpful to stabilize the electricity grid in regions relying on renewable energy sources that have variable and uncertain outputs, such as solar and wind power. Some long-term storage technologies, such as pumped hydroelectric and compressed air energy storage, can store energy for up to approximately 100 hours, while hydrogen can store energy for much longer, such as for seasonal storage. Hydrogen may be able to store large amounts of energy for months or years in underground salt caverns or potentially in depleted oil

[12]North American Electric Reliability Corporation, *Long-Term Reliability Assessment* (January 2026). Department of Energy, *Resource Adequacy Report: Evaluating the Reliability and Security of the United States Electric Grid* (July 7, 2025).

wells.[13] DOE has partnered with several national laboratories to determine the feasibility and risks associated with potential underground hydrogen storage systems.[14]

[13]The Advanced Clean Energy Storage (ACES) project in Utah, which is currently under construction, will use excess renewable energy such as wind and solar to produce hydrogen. The first phase will produce up to 100 tons of hydrogen per day to be stored in salt caverns with 11,000 tons of storage capacity. Hydrogen will be dispatched to local energy producers such as the planned Intermountain Power Project, which will use blended hydrogen and natural gas turbines to produce electricity when demand is high.

[14]DOE's Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project involves three national laboratories to determine the viability, safety, and reliability of storing hydrogen and hydrogen-natural gas blends underground.

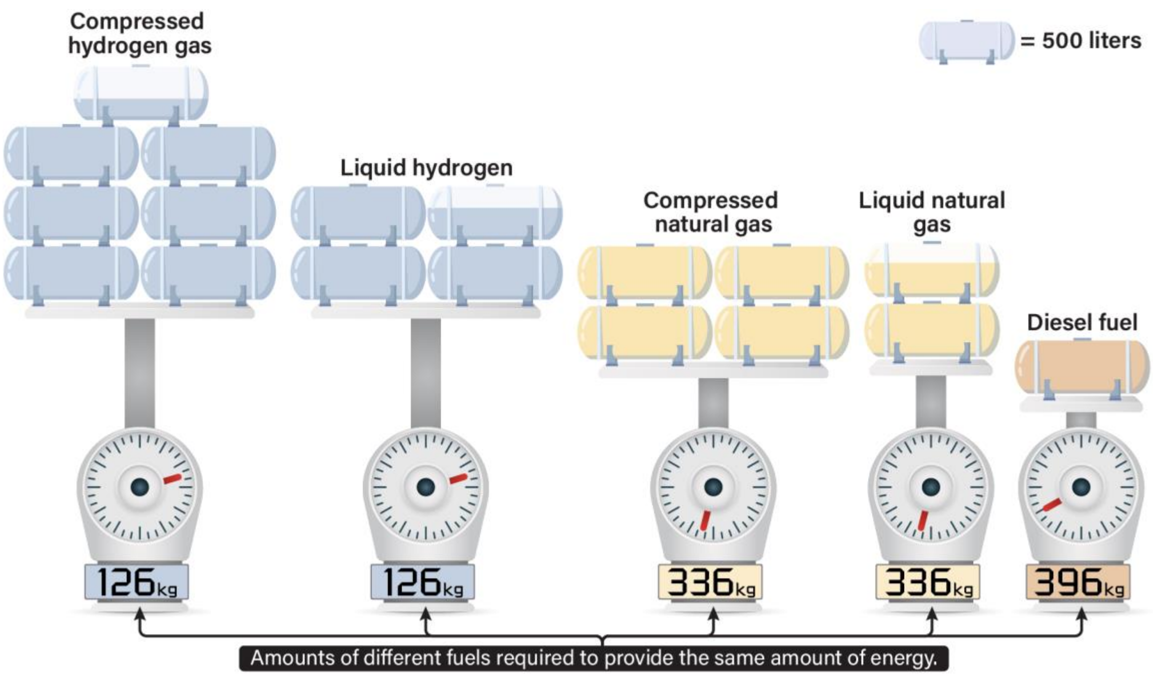
4 Technical Challenges to Widespread Development and Use

We identified four categories of technical challenges that hinder the widespread development or use of hydrogen for energy, some of which have been ongoing for decades. For example, in 1980, we reported that infrastructure constraints limited hydrogen's use as a fuel, a barrier that remains today.[15] Other challenges include efficiency and safety concerns, geographic constraints, and regulations and permitting requirements.

4.1 Efficiency and safety challenges

Compared to other fuels, a larger volume of hydrogen is typically required to provide the same amount of energy (see fig. 6).

Figure 6: Using hydrogen as a fuel saves weight but requires more storage volume



Source: GAO analysis of scientific literature and government reports (data); Goga (scale)/Sensevector (tank)/stock.adobe.com (images). | GAO-26-107932

Note: Depicted weights do not include container weights. Some containers might be heavier than others to meet specific safety, storage duration, and durability needs.

To be effective for energy purposes, hydrogen must be compressed, liquefied, or converted to another chemical—such as ammonia—during transport and storage or for certain end uses. This property gives rise to three challenges that come with using hydrogen energy:

[15]GAO, EMD-80-B3.

Efficiency challenges. Compression, liquefication, and conversion processes all consume energy, which reduces efficiency and increases cost. For example, liquefying hydrogen requires 30 to 36 percent of the energy contained in the hydrogen, compared to approximately 7 to 15 percent for liquefying natural gas.

Leakage and atmospheric effects. The hydrogen molecule is small and can easily leak from transport and storage containers. Leaks may be difficult to detect and leak mitigation measures can increase costs. Leaks may also indirectly affect the atmosphere, because hydrogen gas extends the lifetimes of methane and other greenhouse gases in the atmosphere. Liquid hydrogen stored for long periods of time may require venting some hydrogen to avoid pressure buildup when it is kept at very cold temperatures.[16] The atmospheric effects of hydrogen are not well understood because most of the available data are from modelling and largely focused on hydrogen production.[17] Researchers we spoke with told us that they believe leaks can be prevented with advanced engineering systems, such as those used in established industrial processes that use hydrogen, which could reduce most of the energy efficiency losses. DOE and other stakeholders are researching novel materials that could mitigate some of these storage challenges.[18]

Emergency response considerations. Hydrogen poses detection challenges and unique safety and emergency response considerations. For example, hydrogen fires burn at high speed, do not produce smoke, and can be nearly invisible to the naked eye, which sometimes means that firefighters need a special-purpose camera to see them, although other detection methods exist.[19] And some technologies necessary for mitigating hydrogen-related safety incidents, such as point detection and wide-area monitoring technologies, need wide deployment at facilities that store or use hydrogen. For example, a national laboratory report on a hydrogen leak and fire incident at a California transit agency facility recommended, among other changes, that hydrogen flame detection technologies be evaluated and integrated into existing fire detection systems.[20] However, NASA told us that industry and government have been safely using hydrogen for decades, in addition to updating codes and standards based on lessons learned.[21]

[16]Liquid hydrogen is kept at cryogenic (very cold) temperatures for transport and storage, around -423 degrees Fahrenheit.

[17]International Energy Agency, *Global Hydrogen Review 2024* (Paris, France: Oct. 2024).

[18]One such effort is the Hydrogen Materials Advanced Research Consortium (HyMARC)—comprised of six national laboratories and the National Institute of Standards and Technology—which was created to address scientific gaps with solid-state hydrogen storage materials.

[19]In certain conditions, dust or nearby debris in the air can allow hydrogen flames to be seen more easily by the naked eye.

[20]U.S. Department of Energy, Sandia National Laboratories, *Investigation of the Hydrogen Release Incident at the AC Transit Emeryville Facility*, (Albuquerque, N.Mex. and Livermore, Calif.: June 2012).

[21]For example, see American Institute of Aeronautics and Astronautics and American National Standards Institute, *Guide to Safety of Hydrogen and Hydrogen Systems,* ANSI/AIAA G-095A-2017 (Reston, Va.: Dec. 2017).

4.2 Infrastructure-related challenges

We identified three challenges related to hydrogen infrastructure.

Limited transport and storage infrastructure. Hydrogen transport and storage infrastructure is generally lacking or confined to certain regions of the U.S. For example, hydrogen pipelines are largely confined to the Gulf Coast region. Underground storage is likely the only way to store large amounts of hydrogen for long-duration energy storage (months or longer), but additional research is necessary to better understand the viability of underground sites. Other infrastructure for specific end uses is generally lacking. For example, some states that use hydrogen fuel cell vehicles lack sufficient refueling stations.[22]

Lengthy grid interconnection timelines. It can take years for energy projects, including hydrogen projects, to receive approval to interconnect with the electricity grid, a necessary step for grid applications. Stakeholders from one company we interviewed told us that it can take a decade or more for new connections to join the grid, because of growing domestic energy demand from electric vehicles, data centers, and more. We previously reported on such challenges for energy projects generally.[23]

Embrittlement and other challenges with repurposing infrastructure. Existing infrastructure, such as natural gas pipelines for transport and abandoned oil and gas wells for storage, offer opportunities to expand hydrogen use but might not be suitable in all cases. Hydrogen will penetrate most metals, including structural steels used for pipeline and pressure containing equipment, causing degradation of metal properties, generally known as hydrogen embrittlement.[24] For example, when hydrogen is blended into the existing natural gas pipeline system, hydrogen embrittlement can affect the pipeline and components (such as valves) because they were not designed to accommodate the influence of hydrogen on the structural integrity of the system.[25] (See app. III for additional information on hydrogen-natural gas blending and embrittlement.) Finally, small organisms present in depleted natural gas reservoirs may consume some of the stored hydrogen, similar to processes that

[22]In California, there are approximately 50 refueling stations for hydrogen vehicles as of March 2025, although the state hopes to have 129 stations by 2030. According to national laboratory officials from National Laboratory of the Rockies (previously known as the National Renewable Energy Laboratory), Colorado has only one hydrogen fuel cell vehicle refueling station.

[23]GAO, *Utility-Scale Energy Storage: Technologies and Challenges for an Evolving Grid*, GAO-23-105583 (Washington, D.C.: Mar. 30, 2023).

[24]Embrittlement is a longstanding materials challenge for hydrogen technologies, which we previously reported on. GAO, EMD-79-58.

[25]The oil and gas industry is generally familiar with degradation effects for pipelines that carry different kinds of gases. For example, other pipelines carry sour gas, a type of natural gas blend that contains hydrogen sulfide (H_2S) and carbon dioxide (CO_2), which can introduce phenomena similar to hydrogen embrittlement.

occur with stored natural gas, which can affect the purity.[26]

4.3 Geographic variability limits use of some technologies

Geographic constraints increase costs for some hydrogen users and limit the use of certain transport and storage methods. For example, salt caverns are the only underground structures that have been successfully demonstrated for hydrogen storage at commercial scales. These caverns can maintain large volumes of hydrogen at high purity, but appropriate salt deposits exist only in certain regions, such as along the Gulf Coast (e.g., Texas and Louisiana) and the Rocky Mountains (e.g., Utah). State agency officials from the California Energy Commission told us appropriate geologic conditions for underground hydrogen storage are difficult to find in California. DOE and others have proposed collocating production and end use to limit transport and storage needs and reduce costs (see app. V).

4.4 Regulation and permitting

Regulations and permitting requirements at the federal, state, and local levels can slow down projects.[27] For example, the Federal Energy Regulatory Commission (FERC) has jurisdiction over certain aspects of natural gas pipelines, but according to FERC officials, it is unclear if FERC's existing jurisdictions would cover hydrogen-natural gas blends. In some cases, there are no clear standards for technologies that can use hydrogen for energy. For example, stakeholders from an aviation company told us that they developed their own hydrogen refueling platform and safety protocols because there were no existing standards. According to these stakeholders, the Federal Aviation Administration inspected and approved the company's platform and safety practices.[28] According to experts, hydrogen regulations at the state and local levels are also unclear or unavailable.

[26]Various types of microbes, such as bacteria that consume hydrogen to produce methane or hydrogen sulfide, can survive in underground geologic formations, including natural gas wells. In addition to affecting the purity, these microbes can also affect the stored gases' chemistry, which could change the ways the gases can be used. Determining the specific microbial community for an underground storage site is challenging because researchers have not been able to cultivate many underground microorganisms in the laboratory. For example, see Ianna Gomez Mendez, Waleed M. M. El-Sayed, Anne H. Menefee, and Zuleima T. Karpyn, "Insights into Underground Hydrogen Storage Challenges: A Review on Hydrodynamic and Biogeochemical Experiments in Porous Media," *Energy Fuels*, vol. 38, (2024): 20025.

[27]Several federal agencies may be responsible for oversight over hydrogen, including the Federal Aviation Administration, the Pipeline and Hazardous Materials Safety Administration (PHMSA) within the Department of Transportation (DOT), as well as the Surface Transportation Board and the Federal Energy Regulatory Commission. For example, see U.S. Department of Energy, Sandia National Laboratories, *Federal Oversight of Hydrogen Systems,* (Albuquerque, N.Mex. and Livermore, Calif.: Mar. 2021).

[28]The Federal Aviation Administration told us that it would only have assessed the aircraft as part of its certification process under 14 C.F.R. part 21. Only special airworthiness certificates in the experimental category have been granted for hydrogen-fueled aircraft in the U.S. to date.

5 Hydrogen Energy Policy Environment, Policy Goals, and Policy Options

5.1 The hydrogen policy environment

Since the 1950s, the U.S. has made periodic investments in hydrogen for use as energy and transportation fuel. Past legislation that included hydrogen energy was informed by goals such as energy security and resilience, market competitiveness, and prioritizing use of lower-emission energy technologies (see app. VI). More recently, in 2025, billions of dollars in grants for some clean hydrogen development projects were cancelled, and what is commonly referred to as the One Big Beautiful Bill Act moved up the expiration of a tax credit for new hydrogen production facilities from January 1, 2033, to January 1, 2028.[29] The fluctuating history of natural gas policy and technology development may provide a parallel for hydrogen energy, though natural gas became less expensive than competing energy sources (see text box).

Natural Gas in the U.S.

It took nearly a century of investment, expansion, and innovation to develop today's natural gas system in the U.S. For hundreds of years, natural gas was used for only a few energy applications, such as streetlamps and home heating. One of the first long-distance interstate pipelines was built in 1891, and the system expanded from the 1940s to the 1960s as natural gas was seen as cheaper and cleaner than coal or oil. In the 1970s, policies discouraged the use of natural gas due to a perceived shortage, then deregulation followed in the 1980s. Since the 2000s, technologies such as hydraulic fracturing and horizontal drilling have contributed to a boom in natural gas production. The U.S. now has about 3 million miles of natural gas pipelines, and in 2023 natural gas accounted for 36 percent of primary energy consumption in the U.S.

Sources: U.S. Energy Information Administration (data), literature and government reports (text). | GAO-26-107932

5.2 Policy stability affects outcomes

Stakeholders often refer to the current hydrogen energy policy environment as unstable, which creates uncertainty about wider adoption of technologies that support hydrogen use for energy. Policymakers may have multiple goals, but frequent changes in policy can impede progress toward achieving long term objectives. In some cases, even perceived regulatory instability can reduce new investment and undermine policy goals. For example, a group of researchers at a technology-based university told us that companies that have invested in hydrogen energy are worried about policy changes. Some stakeholders told us about hydrogen energy projects being terminated or companies moving to foreign markets because of policy instability. A nonpartisan, energy-focused organization we spoke with

[29] "Energy Department Announces Termination of 223 Projects, Saving Over $7.5 Billion," U.S. Department of Energy, last modified October 2, 2025, https://www.energy.gov/articles/energy-department-announces-termination-223-projects-saving-over-75-billion. See footnote 6 for a definition of clean hydrogen. See also, An Act to provide for reconciliation pursuant to title II of H. Con. Res. 14, Pub. L. No. 119-21, 139 Stat. 72, 252 (2025), commonly referred to as the One Big Beautiful Bill Act.

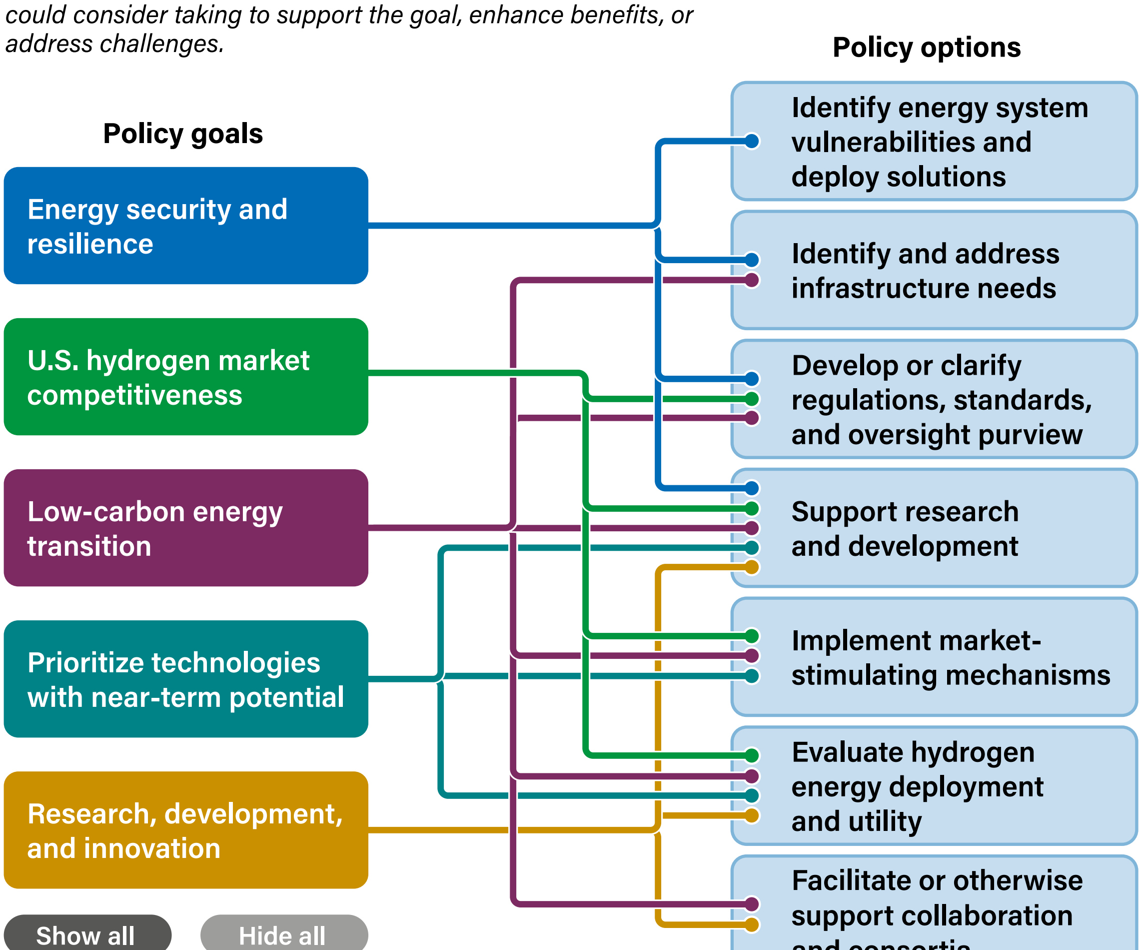
said that the lack of policy stability keeps the price of hydrogen energy high.

5.3 Policy goals for hydrogen energy

We identified five policy goals informed by historical congressional legislation related to hydrogen energy. We also developed seven policy options that various policymakers could consider taking to support these goals (see fig. 7).

Figure 7: Policy goals and supporting policy options

Interactive: *Select a policy goal to see options policymakers could consider taking to support the goal, enhance benefits, or address challenges.*



Source: GAO analysis of literature and government reports (content and illustration). | GAO-26-107932

We present a table for each policy goal with supporting policy options, potential implementation approaches, opportunities the policy option may present, and some considerations. We intend for these goals and options to provide policymakers with a broad base of information for decision-making, but this is not an exhaustive list.

Policy goal: Energy security and resilience

Historical legislation and agency documents state that hydrogen energy can make the energy system less vulnerable, reduce reliance on single or limited resources, preserve energy independence, and strengthen national security.

Table 1: Policy options to support energy security and resilience

Policy option	Opportunities and considerations
Identify energy system vulnerabilities and deploy solutions Potential implementation approach Government policymakers (including federal, state, local, and tribal) could identify critical resource and security vulnerabilities to be mitigated with hydrogen energy technologies. *For example, policymakers could integrate technologies that support the use of hydrogen for energy into emergency preparedness plans and exercises for electricity grid impairments that might result in large-scale loss of power to critical infrastructure.* *For example, federal agencies could support demonstration and deployment of fuel cells at data centers to address near-term electricity demands.*	***Opportunities*** Could diversify the energy system and improve its resiliency. Could make hydrogen more readily available as a tool to build resilience by producing energy independent of existing electricity grid infrastructure. ***Considerations*** May reduce staff and financial resources for more cost effective or mature energy technologies that may provide similar benefits. May require studies to determine circumstances where hydrogen may be the most beneficial option, so resources can be effectively prioritized.
Identify and address infrastructure needs Potential implementation approach Government and private sector policymakers could invest in expanding infrastructure. *For example, federal agencies could de-risk or subsidize deployment of early infrastructure in regions of the country with established demands.* *For example, policymakers could identify which natural gas pipelines or oil and gas wells could be repurposed for hydrogen energy.*	**Opportunities** Could reduce infrastructure limitations and improve hydrogen's competitiveness. ***Considerations*** May reduce resources that could be used for other goals. Existing infrastructure may not be suitable or standardized enough for incorporating hydrogen energy. Development and construction of such infrastructure could have high costs and long time frames, which may be disrupted by changing policy goals and could discourage investors. Federal land management agencies or state governments may raise "best use" concerns if hydrogen were to supersede other resources.

Develop or clarify regulations, standards, and oversight purview Potential implementation approach Government policymakers could ensure there are regulations and standards, and clear oversight jurisdiction over new and existing energy systems and technologies. *For example, federal agencies or state or local governments could simplify or accelerate permitting for energy projects.* *For example, federal agencies could update regulations to address gaps.*	***Opportunities*** Consistent approaches for stakeholders may reduce investor burden and permitting delays. ***Considerations*** Regulators may lack familiarity with or knowledge of some technologies that support the use of hydrogen for energy and may need additional time and resources to clarify regulations, standards, and oversight purview. Resource- or time-intensive regulations or permitting requirements could hinder adoption.
Support research and development (R&D) Potential implementation approach Government, academic, and private sector policymakers could fund R&D for different methods, materials, and technologies to mitigate various hydrogen energy-related challenges. *For example, federal research agencies could support areas of R&D that reduce the barriers to entry for technologies that support the use of hydrogen for energy by improving regulator and utility confidence.* *For example, federal research agencies could sustain and expand areas of R&D related to hydrogen energy integration for improved resilience and modernization of the electricity grid.*	***Opportunities*** Could enable scientific and technological advancements for hydrogen energy—such as geologic hydrogen—and the larger scientific community. May help guide and support other evaluations and decisions about other policy goals, policy options, and implementation approaches. Could produce solutions to technological challenges such as improving component reliability, understanding safety risks, and reducing component costs. ***Considerations*** May reduce resources that could be used for other goals. There is no guarantee that additional R&D will result in deployed technologies.

Source: GAO. | GAO-26-107932

Policy goal: U.S. hydrogen market competitiveness

Global demand for hydrogen is increasing, and the U.S. has diverse and abundant resources to produce and provide hydrogen energy to various sectors and energy markets. Multiple stakeholders and agency officials told us that without federal support for hydrogen energy technologies, the U.S. risks falling behind other countries or regions in global energy markets where hydrogen could play a role. Further, the U.S. faces competition for hydrogen technologies from other countries—for example, China competes with the U.S. in electrolyzer manufacturing.

Table 2: Policy options to support U.S. hydrogen market competitiveness

Policy option	Opportunities and considerations
Implement market-stimulating mechanisms Potential implementation approach Government policymakers (including federal, state, local, and tribal) could introduce economic incentives to promote hydrogen energy technologies or projects in the U.S., or support U.S. commercial interests internationally. *For example, subsidies or other incentives could increase development and adoption of novel technologies that support the use of hydrogen for energy.* *For example, offtake agreements between hydrogen energy producers and consumers could stimulate demand and reduce the risk of projects.*	***Opportunities*** Could help bridge the gap between the higher cost of hydrogen and the price customers are willing to pay. Could motivate the deployment of a low-carbon energy transition while taking advantage of mature technologies that face cost barriers. Could encourage competition in foreign markets that impose penalties for exceeding a specified limit on carbon emissions. ***Considerations*** Inconsistent or fluctuating incentives could encourage producers and consumers to continue using fossil fuel technologies. There may not be sufficient or available transport and storage methods to support increased supply and demand.
Develop or clarify regulations, standards, and oversight purview Potential implementation approach Government, academic, and private sector policymakers could ensure there are energy system and technology regulations and standards, and clear oversight jurisdiction. *For example, policymakers could simplify or accelerate permitting for energy projects.* *For example, a national laboratory or trusted third party could develop or consolidate resources for regulators or industry stakeholders, such as case studies on how specific deployments could be permitted or a database of state and local regulatory requirements.*	***Opportunities*** Consistent approaches for stakeholders may reduce investor burden and permitting delays. ***Considerations*** Regulators may lack familiarity with or knowledge of some technologies that support the use of hydrogen for energy and may need additional time and resources to clarify regulations, standards, and oversight purview. Resource- or time-intensive regulations or permitting requirements could hinder adoption.
Support research and development (R&D) Potential implementation approach Government, academic, and private sector policymakers could fund R&D for different methods, materials, and	***Opportunities*** Could enable scientific and technological developments and advancements for hydrogen energy technologies and the larger scientific community.

technologies for hydrogen that support U.S. commercial or strategic interests. *For example, policymakers could support R&D of hydrogen energy technologies that may be attractive to global markets.* *For example, a federal agency or national laboratory could support pilot projects to advance emerging technologies that support the use of hydrogen for energy to commercial scale.*	May help guide and support other evaluations and decisions about other policy goals, policy options, and implementation approaches. ***Considerations*** May reduce staff and financial resources that could be used for other opportunities or policy goals. There is no guarantee that additional R&D will result in reduced costs or deployed technologies.
Evaluate hydrogen energy deployment and utility Potential implementation approach A federal agency, federally funded R&D center, a government-sponsored task force, a nonprofit organization, or another trusted entity could conduct economic studies to identify potential markets for technologies that support the use of hydrogen for energy. *For example, the Department of Energy (DOE), national laboratories, industry stakeholders, or a trusted third party, could conduct studies on which technologies that support the use of hydrogen for energy are well-suited for export.* *For example, federal research agencies, national laboratories, industry stakeholders, or a trusted third party, could conduct studies of geologic hydrogen or other nascent technologies to assess their potential for further development.*	***Opportunities*** Could help identify *where* and *when* to use hydrogen energy and inform decisions about which other policy goals and policy options to pursue. ***Considerations*** May reduce resources that could be used for other goals. The value of such assessments can vary.

Source: GAO. | GAO-26-107932

Policy goal: Low-carbon energy transition

Many efforts to expand the use of hydrogen energy have considered the potential to reduce carbon emissions in the current energy system. Agency officials, researchers, experts, and companies we spoke with were interested in hydrogen as a low-carbon energy alternative.

Table 3: Policy options to support low-carbon energy transition

Policy option	Opportunities and considerations
Implement market-stimulating mechanisms Potential implementation approach Government policymakers (including federal, state, local, and tribal) could introduce economic incentives to scale low-carbon energy technologies. *For example, carbon pricing or tax incentives for certain technologies could increase interest in and adoption of clean technology innovation and utilization, such as carbon capture and sequestration, pyrolysis, or electrolytic hydrogen.* *For example, offtake agreements between hydrogen energy producers and consumers could stimulate demand for low-carbon hydrogen.*	***Opportunities*** Could help bridge the gap between the higher cost of low-carbon hydrogen and the price customers are willing to pay. Could motivate the deployment of a low-carbon energy transition while taking advantage of mature technologies that face cost barriers. ***Considerations*** Inconsistent or fluctuating incentives could encourage producers and consumers to continue using fossil fuel technologies. There may not be sufficient transport and storage methods to support increased supply and demand.
Identify and address infrastructure needs Potential implementation approach Government and private sector policy makers could invest in expanding infrastructure. *For example, policymakers could invest in the expansion of low-carbon energy technology infrastructure, such as dedicated hydrogen pipelines.* *For example, government or private sector policy makers could invest in regional hubs that support low-carbon energy technologies, such as the Department of Energy (DOE) Hydrogen Hub program.* *For example, federal agencies could partner with private sector or national laboratories to assess current infrastructure for low-carbon energy technologies, identifying gaps and areas for expansion.*	***Opportunities*** May enable wide-scale adoption of hydrogen energy technologies and reduce infrastructure limitations between steps in the supply chain. ***Considerations*** May reduce staff and financial resources that could be used for other opportunities or policy goals. Development and construction of infrastructure could have high costs and long time frames. Changing policy goals could disrupt and discourage long-term investments and projects.
Develop or clarify regulations, standards, and oversight purview Potential implementation approach Government, academic, and private sector policy makers could ensure that there are energy system and technology regulations and standards, and clear oversight jurisdiction *For example, federal regulatory agencies could work with Congress, industry, and others to proactively assess appropriate oversight and regulatory jurisdiction.* *For example, private companies and federal agencies*	***Opportunities*** Existing standards can be used as a model, adjusted to accommodate low-carbon and hydrogen energy technologies Consistent approaches for stakeholders may reduce investor burden and permitting delays. ***Considerations*** Not all low-carbon energy technologies may be

could work together to develop fueling protocols and safety and inspection standards for new technologies, such as hydrogen-powered trucks or aircraft.	viable across regions. Regulators may lack familiarity with or knowledge of some technologies that support the use of hydrogen for energy and may need additional time and resources to clarify regulations, standards, and oversight purview. Resource- or time-intensive regulations or permitting requirements could hinder adoption.
Support research and development (R&D) Potential implementation approach Government, academic, and private sector policy makers could fund R&D for different methods, materials, and technologies that support a low-carbon energy transition. *For example, federal research agencies may provide grants to companies, national laboratories, or researchers to support development, demonstration, and deployment of technologies that support the use of hydrogen for energy.* *For example, federal research agencies or national laboratories could perform R&D to identify low-carbon hydrogen production methods, or chemicals and materials to improve hydrogen transport and storage.*	***Opportunities*** Could enable scientific and technological developments and advancements for low-carbon hydrogen energy and the larger scientific community. May help guide and support other evaluations and decisions about other policy goals, policy options, and implementation approaches. ***Considerations*** May reduce staff and financial resources that could be used for other opportunities or policy goals. There is no guarantee that additional R&D will result in reduced costs or deployed technologies.
Evaluate hydrogen energy deployment, and utility Potential implementation approach A federal agency, federally funded R&D center, government-sponsored task force, a nonprofit organization, or other trusted entity could conduct techno-economic assessments. *For example, DOE, the Department of Transportation, or a trusted third-party, such as the National Academies of Science, Engineering and Medicine could identify the most appropriate and cost-effective low carbon technologies, such as hydrogen energy production methods.*	***Opportunities*** Could help identify *where* and *when* to use clean hydrogen energy and inform decisions about which other policy goals and policy options to pursue. ***Considerations*** May reduce resources that could be used for other goals. The value of such assessments can vary
Facilitate or otherwise support collaboration and consortia Potential implementation approach Federal agencies, industry partners, nonprofits, researchers, and other interested stakeholders could form a task force, a nonprofit organization, or another	***Opportunities*** Broad dissemination of institutional knowledge could help address known challenges, such as those related to efficiency and safety, and innovate on existing technologies. Could help align technology development, test resources, and regulatory changes. Leveraging existing facilities and subject-matter experts

trusted entity to lead collaborative partnerships for knowledge sharing and leadership. *For example, federal agencies could collaborate to advance a whole-of-government approach to support a national low-carbon hydrogen energy strategy.* *For example, academic studies about hydrogen energy production, transport, storage, and end-use technologies could be compiled into an accessible compendium to facilitate knowledge sharing and technology advancement.*	minimizes the need for new resource investments. ***Considerations*** Benefits derived from collaborative efforts may not be equally shared among those involved. There is no guarantee that collaboration will result in material benefit.

Source: GAO. | GAO-26-107932

Policy goal: Prioritize technologies with near-term potential

Some federal agencies and research institutions measure and track technology readiness levels, assessing the maturity level of a particular technology at different stages of its development. Though some hydrogen technologies are mature, there are some that have much longer time horizons, including those that require the development of more transport and storage infrastructure for wider adoption.

Table 4: Policy options to support prioritizing technologies with near-term potential

Policy option	Opportunities and considerations
Implement market-stimulating mechanisms Potential implementation approach Government policymakers (including federal, state, local, and tribal) could introduce economic incentives to scale specific technologies. *For example, Congress could offer temporary tax credits for energy technologies that are ready to deploy.*	***Opportunities*** Could help bridge the gap between the higher cost of hydrogen and the price customers are willing to pay. ***Considerations*** The most mature technologies may not be competitive in global markets or may not have many utilization opportunities.
Support research and development (R&D) Potential implementation approach Government and private sector policymakers could streamline energy technology R&D. *For example, a national laboratory or federal agencies may redirect funding from projects with long time horizons to more mature technologies.*	***Opportunities*** Could streamline R&D for technologies on the cusp of commercialization while enabling scientific and technological advancements for hydrogen energy and the larger scientific community. May help guide and support other evaluations and decisions about other policy goals, policy options, and implementation approaches.

For example, federal research agencies or a national laboratory could focus their efforts on prototyping, testing, and demonstrating energy technologies with the highest potential for commercial opportunities.	***Considerations*** May reduce staff and financial resources that could be used for other opportunities or policy goals. There is no guarantee that additional R&D will result in deployed technologies.
Evaluate hydrogen energy deployment and utility Potential implementation approach A federal agency, federally funded R&D center, government-sponsored task force, a nonprofit organization, or other trusted entity could conduct assessments to identify mature technologies that support the use of hydrogen for energy. *For example, national laboratories and industry could identify technology readiness levels of technologies that support the use of hydrogen for energy.*	***Opportunities*** Could help identify *where* and *when* to use hydrogen energy and inform decisions about which other policy goals and policy options to pursue. ***Considerations*** May reduce resources that could be used for other goals. The value of such assessments can vary.

Source: GAO. | GAO-26-107932

Policy goal: Research, development, and innovation

NASA, DOE, USGS, DOT, and several commercial companies have efforts underway to support the research, development, and innovation of hydrogen energy production, transport, storage, and end-use technologies.

Agency officials and experts we spoke with were in broad agreement that additional research, development, and innovation are needed to advance the adoption of hydrogen energy technologies.

Table 5: Policy options to support research, development, and innovation

Policy option	Opportunities and considerations
Support research and development (R&D) Potential implementation approach Government (including federal, state, local, and tribal) and private sector policymakers could fund R&D for different methods, materials, and technologies to mitigate various hydrogen energy-related challenges. *For example, a national laboratory could continue or expand research into novel hydrogen storage methods that address risks.*	***Opportunities*** Could enable scientific and technological developments and advancements for hydrogen energy and the larger scientific community. May help guide and support other evaluations and decisions about other policy goals, policy options, and implementation approaches. ***Considerations*** May reduce staff and financial resources that could be used for other opportunities or policy goals. There is no guarantee that additional R&D will result in deployed technologies.
Evaluate hydrogen energy deployment and utility	***Opportunities*** Could help identify *where* and *when* to use

Potential implementation approach A federal agency, federally funded R&D center, government-sponsored task force, a nonprofit organization, or another trusted entity could conduct techno-economic assessments. *For example, DOE, the Department of Transportation, or a trusted third party, such as the National Academies of Sciences, Engineering, and Medicine, could identify the most appropriate and cost-effective applications of technologies that support the use of hydrogen for energy.*	hydrogen energy and inform decisions about which other policy goals and policy options to pursue. ***Considerations*** May reduce resources that could be used for other goals. The value of such assessments can vary.
Facilitate or otherwise support collaboration and consortia Potential implementation approach A federal agency, federally funded R&D center, government-sponsored task force, nonprofit organization, or another trusted entity could lead collaborative partnerships for knowledge sharing and other efforts to advance hydrogen energy endeavors. *For example, federal research agencies and industry could partner with the national laboratories to use their dedicated hydrogen laboratory space and knowledge.*	***Opportunities*** Broad dissemination of institutional knowledge could help address known challenges, such as those related to safety, and innovate on existing technologies. Could help align technology development, test resources, and regulatory changes. Leveraging existing facilities and subject-matter experts minimizes the need for new resource investments. ***Considerations*** Benefits derived from collaborative efforts may not be equally shared among those involved. There is no guarantee that collaboration will result in material benefit.

Source: GAO. | GAO-26-107932

6 Agency and Expert Comments

We provided a draft of this report to DOE, Department of the Interior, Department of Transportation, the Energy Information Administration, FERC, and NASA with a request for technical comments. We incorporated agency comments into this report as appropriate.

We also provided a draft of this report to 10 experts who participated in our review, and incorporated comments as appropriate.

We are sending copies of this report to the appropriate congressional committees and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard, PhD, at HowardK@gao.gov. Contact points for our Offices of Congressional Relations and Media Relations may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix VII.

//signed//

Karen L. Howard, PhD
Director
Science, Technology Assessment, and Analytics

List of Congressional Addressees

The Honorable Sharice Davids
House of Representatives

The Honorable Carol D. Miller
House of Representatives

Appendix I: Objectives, Scope, and Methodology

Objectives

We prepared this report at the initiative of the Comptroller General to assist Congress with its oversight responsibilities, in light of the evolving hydrogen energy technology and policy environment. Specifically, we focused on hydrogen energy technologies across four steps in the supply chain—production, transport, storage, and end use—that could enable the use of hydrogen for energy. For this report, we described the potential benefits and status of available or developing hydrogen energy technologies, described the challenges of developing or using these technologies, and identified policy goals that policymakers could pursue through various policy options that could help realize benefits or address challenges. Specific objectives for this report were:

- What are the current and emerging technologies for hydrogen energy production, transport, storage, and use?
- What are the potential benefits and challenges to developing or using such hydrogen energy technologies?
- What policy options, if any, could help support a range of policy goals?

Scope

We limited the scope of this technology assessment to technologies that support the use of hydrogen for energy. We also primarily focused on U.S. projects, companies, and policies.

Methodology

For all objectives, we reviewed literature and agency documents; interviewed a variety of agency officials, industry representatives, and other stakeholders; conducted site visits; attended an energy transition conference; and convened a 3-day meeting of experts. For objective 3 (in addition to the steps above), we identified five policy goals from past legislation and policy options that could support each goal.

Review of literature and documents

For all objectives, we reviewed relevant literature and documents identified by agency officials, stakeholders, and our literature search. A GAO librarian conducted a background literature search to find information on hydrogen energy using databases such as EBSCO, OSTI, Lexis+, and Scopus. We narrowed our search to articles published since 2020 to capture recent developments in hydrogen energy. Results of the search included scholarly or peer-reviewed material; government reports; trade or industry papers; and association, nonprofit, and think-tank publications. We selected articles most relevant to our objectives for further review.

The literature and documents provided information and knowledge for our understanding of the state of hydrogen energy technologies, helped us identify expert individuals or groups to interview or consider for the meeting of experts, and provided additional context for what we heard during the interviews. In addition to our search, we received literature and documents from agency officials and other stakeholders we interviewed.

Interviews and site visits

For all objectives, we conducted semi-structured interviews with a range of stakeholders to ensure balance across different perspectives. We tailored some of the interview questions based on the interviewees' roles, responsibilities, and expertise. We identified groups or individuals to interview who had relevant expertise in areas identified through our review of background literature, attending an energy transition conference, and from recommendations from other interviewees. We selected our interviewees to complement the other parts of our methodology, such as verifying key information from literature and documents and supplementing the views provided by our expert participants. In our report, we refer to individuals representing an agency as "agency officials," individuals who participated in our expert meeting as "experts," and those we interviewed as "stakeholders." When statements include a mix of these individuals, we attribute them to "stakeholders."

We interviewed federal officials at the agencies primarily involved with supporting or regulating hydrogen energy activities, including senior-level officials or technical experts from the Department of Energy (DOE), Energy Information Administration, Federal Energy Regulatory Commission (FERC), National Aeronautics and Space Administration (NASA), Department of Transportation, and Department of the Interior.

We also interviewed industry representatives from organizations that represent the hydrogen energy sector and other companies based on the relevance of their activities to our scope. We interviewed several officials at multiple federally funded research and development centers who are actively involved in developing hydrogen energy technologies and policy.

We conducted 12 of these interviews in person as part of site visits to observe test facilities and hydrogen energy technologies under development. Because we interviewed and visited a nongeneralizable sample of stakeholders, the results of our interviews and site visits are illustrative and represent important perspectives but are not generalizable.

Meeting of experts

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a 3-day, virtual expert meeting to help provide additional context and information for the evidence we obtained from literature, documents, and interviews; facilitate discussion of the potential benefits and challenges of developing and using hydrogen energy technologies; develop policy options to support various policy goals; and discuss opportunities and considerations of those policy options. We divided the meeting into moderated sessions during which the experts were asked open-ended questions, such as the current state of technologies, the primary challenges facing the deployment of those technologies, and actions that policymakers could take.

The meeting included a nongeneralizable group of 18 experts from government agencies, industry, academia, and federally funded research and development centers. The experts and their titles and affiliations are listed in appendix II. We selected the experts based on their technical, legal, business, or policy expertise so that the group would include a balanced and diverse set of views from government, nongovernmental organizations, industry representatives, and academic researchers. Prior to the meeting, we asked the experts to identify any potential conflicts of interest, which we considered to be any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair advantage for any person or organization. We determined the 18 experts to be free of reported conflicts of interest, except those that were outside the scope of the meeting or where the overall design of our meeting and methodology was sufficient to address them for our purpose. We also judged the group as a whole to have no inappropriate biases for our purpose. The comments of these experts generally represented their individual views and not the organizations with which they were affiliated and are not generalizable to the views of others in the field.

The meeting was professionally transcribed to ensure that we accurately captured the experts' statements. Following the meeting, we continued to draw on the expertise of those individuals who agreed to work with us during the remainder of our study, as explained further in appendix II. We provided the experts an opportunity to provide feedback on potential policy options and implementation approaches. We also provided the experts an opportunity to review a draft of our report and provide technical comments, which we incorporated as appropriate.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a meeting of experts to discuss the opportunities and challenges of hydrogen energy technologies and inform the development of policy options. All final decisions regarding meeting substance and expert participation were made by GAO. The meeting was held virtually in July 2025.

The 18 experts who participated in this meeting are listed below, along with their titles at the time of the meeting. We sent the report to 10 of those experts who volunteered to review it, and we incorporated their comments as appropriate.

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Appendix III: Hydrogen-Natural Gas Blending: Status, Benefits, and Challenges

Hydrogen can be blended with natural gas—currently in small quantities—and distributed via the natural gas pipeline system ("blending"). Depending on the intended end use, hydrogen can be separated from the natural gas or remain blended.[30]

Status of blending and federal efforts

Current status across the U.S.

Blending projects have been undertaken or announced in at least four states, as well as between the U.S. and Canada. As of October 2022, utilities companies in California, Hawaii, and New Jersey have successfully demonstrated blending hydrogen into natural gas transmission or distribution lines, according to a national laboratory report.[31]

California

- In 2021, a California utility company conducted a pilot project delivering a 20 percent hydrogen-natural gas blend in a closed-loop system for residential energy needs.
- In response to California Senate Bill 1369, the California Public Utilities Commission sponsored a study to assess the operational and safety concerns associated with injecting hydrogen at various percentages into the existing natural gas pipeline system in California.[32]

Colorado

- In 2023, a utility company in Colorado announced plans to blend small amounts of hydrogen (up to 10 percent) into its natural gas system. According to news reports, the company later delayed, then cancelled these plans, in response to a Colorado Public Utilities Commission decision.

Hawaii

- Since 1970, a utility company in Hawaii has successfully used a form of blended synthetic natural gas that contains hydrogen (up to 15 percent) in natural gas distribution and transmission pipelines.[33]

New Jersey

- Since 2021, a New Jersey utility company has been researching injecting small

[30]Certain end uses could use a hydrogen-natural gas blend, such as residential or commercial boilers and furnaces. Other end uses likely require pure hydrogen, such as hydrogen fuel cell vehicles.

[31]National Renewable Energy Laboratory (NREL), *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology,* Technical Report NREL/TP-5400-81704 (Golden, C: October 2022).

[32]The California Public Utilities Commission*, FINAL REPORT: Hydrogen Blending Impacts Study,* R.13-02-008 (San Francisco, CA: July 18, 2022).

[33]Synthetic natural gas is chemically similar to natural gas and is produced from coal, biomass, and other hydrocarbon-based sources. For example, see Hawaii Gas, *Hawaii Revised Statutes (HRS) § 269-45, Gas Utility Companies Renewable Energy Report*, prepared for the Hawaii Public Utilities Commission (Honolulu, HI: March 31, 2023).

amounts (less than 1 percent) of hydrogen into a natural gas distribution pipeline.

U.S. and Canada

- Since 2015, at least two projects have been undertaken to understand the effects and leakage potential of hydrogen-natural gas blending on international pipelines between the U.S. and Canada.

Selected federal efforts

- The Department of Energy's (DOE) HyBlend initiative aims to address technical barriers to blending hydrogen with natural gas for distribution via existing pipelines. HyBlend's efforts include materials compatibility research and development, techno-economic analysis, and life cycle analysis to inform the development of publicly accessible tools that characterize the opportunities, costs, and risks of blending.[34]
- On March 25, 2024, the Pipeline and Hazardous Materials Safety Administration (PHMSA), within the Department of Transportation (DOT), published to the Federal Register a notice and request for comments regarding blending hydrogen gas and natural gas within gas pipelines. PHMSA proposed modifying multiple reporting forms to allow gas pipeline operators to select one of three new proposed blending percentage values: (1) greater than 0 percent but less than or equal to 5 percent; (2) greater than 5 percent but less than 20 percent; and (3) greater than or equal to 20 percent.[35] DOT officials told us that PHMSA is currently analyzing public comments for consideration.
- In 2022, researchers from the National Renewable Energy Laboratory (now called the National Laboratory of the Rockies), Sandia National Laboratories, Pacific Northwest National Laboratory, and the University of Colorado Boulder published a review of the state of blending technology, including research status, discussion of relevant models, and challenges.[36]

Benefits of blending

Increased renewable energy output. Blending has been proposed as way to increase the output of renewable energy systems, such as large wind farms, by using excess power to produce hydrogen for subsequent energy needs. Blending would help to distribute this excess power by using hydrogen as the energy carrier.

Reduced greenhouse gas emissions. If the blended hydrogen is produced from low-carbon energy sources, it could reduce the overall greenhouse gas emissions of the hydrogen-natural gas blend. However, the benefit of reduced emissions provided by

[34]HyBlend is the colloquial name for Pipeline Blending Cooperative Research and Development Agreement, which is co-funded by industry through partnership with the Pipeline Research Council International and includes major international oil and gas companies to address pipeline material compatibility and degradation, techno-economic analysis, and life cycle assessment of blending impacts.

[35]89 Fed. Reg. 20,751 (Mar. 25, 2024).

[36]NREL, *Hydrogen Blending*.

hydrogen is disputed and may only be meaningful at high blend percentages.

Lower-cost hydrogen transport. Blending has the potential to be a lower-cost transport option, instead of building new, expensive dedicated hydrogen pipelines or truck or train transport.

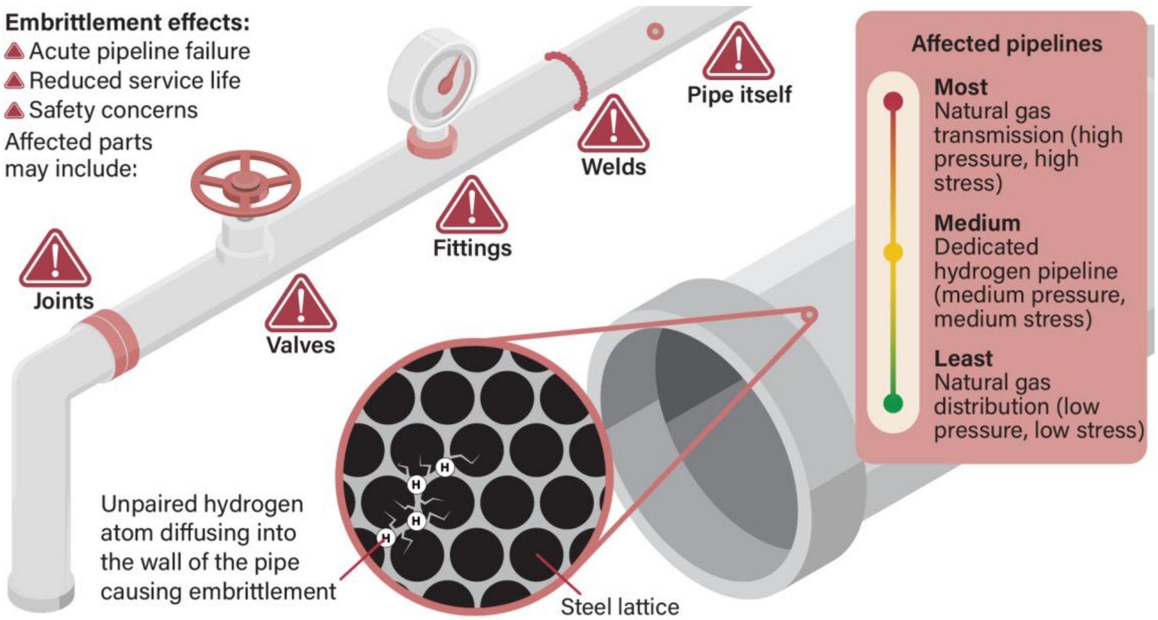
Shorter timeline for large-scale deployment. Rather than building new infrastructure, repurposing existing pipelines could shorten timelines for large-scale hydrogen energy projects.

Challenges of blending

Embrittlement. Blending hydrogen into natural gas pipelines can exacerbate existing flaws and cause cracks and fatigue to pipelines and components—a phenomenon known as hydrogen embrittlement (see 3.3 and fig. 8). Experts told us that embrittlement depends on factors such as pressure, design, and materials. Further, the construction and operational history of natural gas pipelines may not be well known. Studies have shown that lower-strength metals can generally resist fractures better than higher-strength metals when in contact with hydrogen. Higher-strength steel pipes are generally used for higher-pressure natural gas transmission lines but are classified as low-strength steel (e.g., compared to some steels used for hydrogen storage). Natural gas distribution lines generally use commodity-grade, low-strength steels or plastic pipe. Dedicated hydrogen pipelines' design, quality controls (such as welding and inspection), and use of specific steels and other materials allow them to reduce the effects of embrittlement.[37]

[37]For example, see American Society of Mechanical Engineers, *Hydrogen Piping and Pipelines,* ASME B31.12 - 2023 (New York: N.Y.: 2024).

Figure 8: **Hydrogen embrittlement**



Source: GAO analysis of literature and government reports (content); GAO (graphic elements); Allafoto/stock.adobe.com (images). | GAO-26-107932

Lack of standards. A lack of quality and interchangeability standards for hydrogen-natural gas blends for interstate pipelines could impede a nationwide hydrogen blending strategy.[38]

Additional research necessary. According to a national laboratory report, substantial additional research is necessary before widespread hydrogen blending could occur.[39] For example, technologies designed to detect leaks in natural gas pipelines may not function as designed if hydrogen is introduced into the pipeline.

Combustion effects. Depending on the intended end use, blending could cause transport and operational challenges because hydrogen and natural gas have different combustion properties and certain technologies were designed for natural gas. For example, compressor stations along pipelines use a small amount of gas present in the pipeline to function, and these stations could be impacted by hydrogen's influence on the combustion of the blended fuel as well as the compatibility of the materials of the compressor

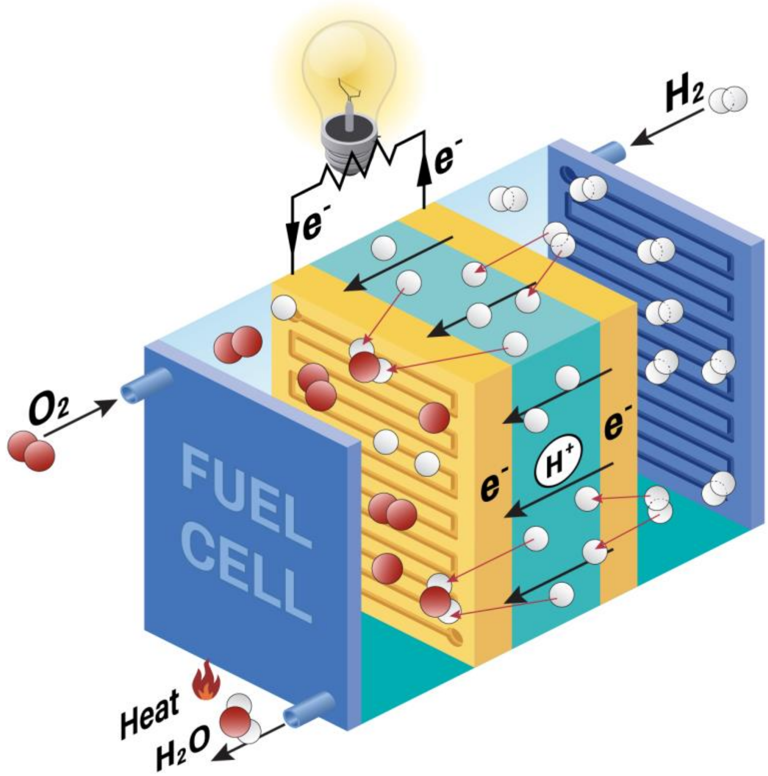
[38]See Congressional Research Service, *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, R46700 (Washington, D.C.: March 2, 2021). The American Society of Mechanical Engineers is updating the code for natural gas transmission and distribution pipelines to include hydrogen. Standards in other areas may be lagging, such as for metering and detection.

[39]NREL, *Hydrogen Blending*.

Appendix IV: Hydrogen Fuel Cell

Fuel cells create electricity through a chemical reaction between a fuel and an oxidizing agent (a chemical that gains electrons from another chemical in the reaction). Similar to batteries, fuel cells have a positive and negative terminal separated by a chemical barrier that allows current to pass (see fig. 9). Individual fuel cells can be combined together in “stacks” to create the amount of power needed for the application—more fuel cells produce more power. Fuel cells can continue operating as long as fuel and air are provided, unlike batteries which are limited by a fixed amount of charge inside the battery. Fuel cells can generally use different fuels, such as natural gas, hydrogen, and others.

Figure 9: Hydrogen proton exchange membrane fuel cell



Source: GAO analysis of scientific literature and government reports (data); GAO (graphic elements); macrovector (light)/sivvector (fuel cell)/ stock.adobe.com (images). | GAO-26-107932

Hydrogen fuel cells combine hydrogen gas with oxygen to produce electricity while producing heat and water as byproducts. Fuel cells are versatile and can power a wide range of applications, including hand-held devices, generators, and automobiles. Fuel cells are typically up to twice as efficient as traditional internal combustion engines. The Department of Energy, national laboratories, and other scientists conduct research on hydrogen fuel cells to reduce costs and improve their performance and durability.

Appendix V: Hydrogen Energy Collocation

The distance between hydrogen production facilities and end users may be vast. Placing hydrogen production and end use relatively close to one another—known as collocation—can reduce this distance. Two methods of collocation include:

- **Onsite production and end use.** One method involves placing hydrogen production and end use physically close to one another, which reduces the need for hydrogen transport and storage mechanisms. For example, one company we spoke with offers a containerized, modular hydrogen production and storage system that allows customers to produce hydrogen onsite. Such a system could be used to provide onsite hydrogen for commercial fleet fuel cell vehicles, such as trucks or buses, according to company stakeholders.
- **Regional collocation.** Another method involves designing regional networks where hydrogen production and end users are close enough to limit transport and storage infrastructure needs. In general, infrastructure to transport and store hydrogen is limited and large-scale hydrogen production and transport capabilities are currently limited primarily to the Gulf Coast region and California. For example, most of the country's dedicated hydrogen pipelines—approximately 2,011 miles—that facilitate transport of hydrogen to end users are located in the Gulf Coast.[40] In California, there is production and storage infrastructure, as well as truck fleets for transport. In 2023, the Department of Energy (DOE) announced its Hydrogen Hubs program and is pursuing regional collocation as one strategy for the hubs.[41] These hubs were designed to address logistical challenges by creating regional networks of hydrogen producers, potential hydrogen consumers, and connective infrastructure located in close proximity.[42]

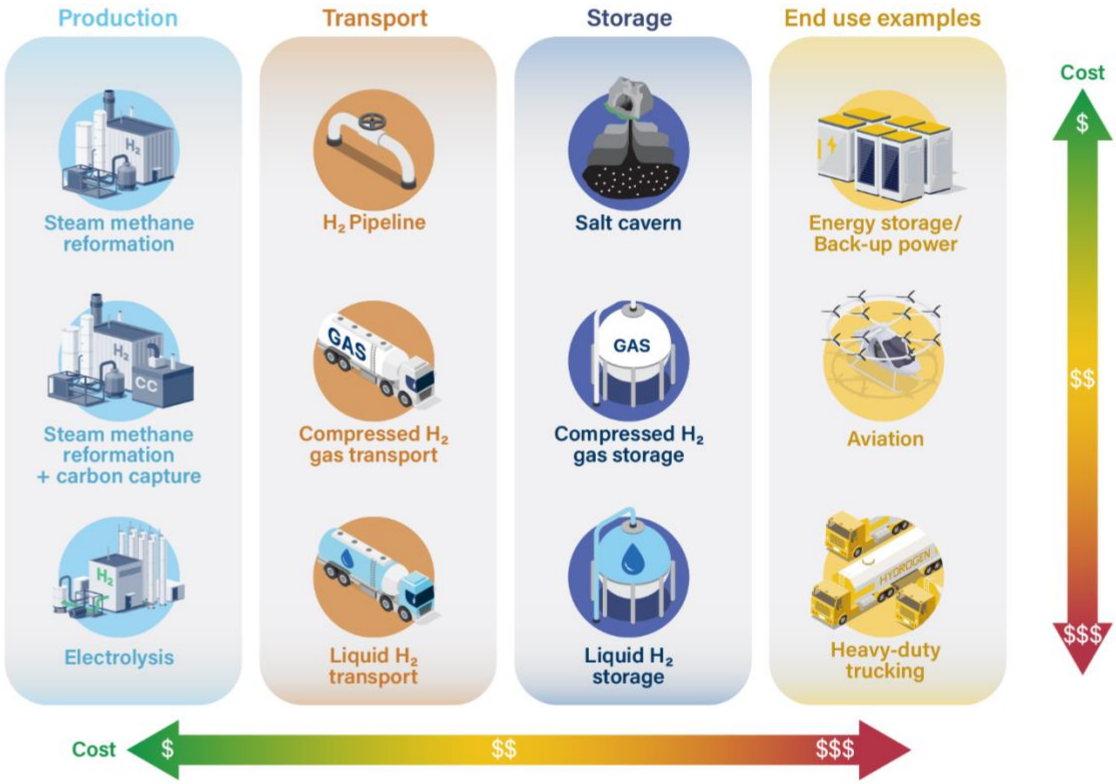
Figure 10 illustrates how each step in the hydrogen supply chain contributes to the cost of hydrogen energy, according to DOE 2023 and 2024 reports, *Pathways to Commercial Liftoff: Clean Hydrogen*. In some cases, transporting and storing hydrogen can roughly double the cost, and the infrastructure for both of these supply chain steps is generally lacking (see 4.2). When collocation is feasible, it can reduce costs, limit hydrogen's life cycle emissions, and offer energy to end users without the need for grid electricity.

[40]Of the approximately 2,011 miles of hydrogen pipelines, 1,617 miles are regulated federally by the Pipeline and Hazardous Materials Safety Administration (PHMSA) within the Department of Transportation, as of February 2026; and 394 miles fall outside of PHMSA's jurisdiction. By comparison, the natural gas system in the U.S. has approximately 3 million miles of pipeline.

[41]In 2021, the Infrastructure Investment and Jobs Act authorized $8 billion to establish Regional Clean Hydrogen Hubs across the U.S. See Pub. L. No. 117-58, 135 Stat. 429, 1010 (2021). This program is administered by DOE, which has committed or obligated most of the authorized funds since 2021.

[42]U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (Washington, D.C.: June 2023).

Figure 10: Notional examples of how each step in the supply chain contributes to the cost of hydrogen energy



Source: U.S. Department of Energy reports; GAO (graphic elements); Petrovarga (production and energy storage)/Macrovector (pipeline, storage, transport, aviation, trucking)/Ylivdesign (cave)/stock.adobe.com (images). | GAO−26−107932

Note: The relative positions of specific technologies at each step of the supply chain indicate one technology as more or less costly, on a dollar per kilogram of hydrogen basis, as reported as reported in DOE's Mar. 2023 and Dec. 2024 *Pathways to Commercial Liftoff: Clean Hydrogen* reports. Production technologies represent 2023 costs; and transport, storage and end-use technologies represent projected 2030 costs.

Appendix VI: Selected Historical Congressional Support for Hydrogen Energy

Table 6: Selected historical congressional support for hydrogen energy

Year	Support	Legislation	Selected Policy Goal(s)
1954		Congress authorized $2.5 million used for the **U.S. Space Program's Rocket Engine Test Facility** at its Lewis Flight Propulsion Laboratory to test liquid hydrogen rocket engines.	• Research, development, and innovation
1976		Congress authorized $30 million for the **Hydrogen Program through the Electric and Hybrid Vehicle Research, Development, and Demonstration Act** to encourage and support accelerated research and development of electric and hybrid vehicle technologies.	• Energy security and resilience • Research, development, and innovation • Prioritize proven, market-ready technologies • Low-carbon energy transition
1979		The **Hydrogen Fuel Development and Use Act of 1979** was introduced in the House of Representatives to support research, development, and demonstration of hydrogen production and end-use technologies, but did not progress beyond Committee.	• U.S. hydrogen market competitiveness • Research, development, and innovation
1990		Congress authorized $20 million for hydrogen research and development through the **Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990**.	• Energy security and resilience • U.S. hydrogen market competitiveness • Low-carbon energy transition • Research, development, and innovation
1996		Congress authorized $214.5 million for hydrogen research, development, and	• U.S. hydrogen market competitiveness

		demonstration programs under the **Hydrogen Future Act**.	• Prioritize proven, market-ready technologies • Research, development, and innovation
2005		Congress authorized nearly $2 billion for projects and activities related to hydrogen production, storage, distribution and dispensing, transport, and education projects, and projects and activities related to fuel cell technologies under the **Energy Policy Act of 2005**.	• U.S. hydrogen market competitiveness • Research, development, and innovation
2009		Congress cut $100 million from the Fuel Cell Technologies program), reducing it by nearly 60% through the **Energy and Water Development and Related Agencies Appropriations Act, 2009**.	• Energy security and resilience • Prioritize technologies with near-term potential
2022		In what is commonly referred to as the **Inflation Reduction Act**, Congress provided a clean hydrogen tax credit of up to $3 per kilogram of qualified clean hydrogen produced by qualified clean hydrogen production facilities constructed through 2032.	• U.S. hydrogen market competitiveness • Low-carbon energy transition
2025		Congress limited the hydrogen tax credits to qualified clean hydrogen production facilities that begin construction by the end of 2027 in what is commonly referred to as the **One Big Beautiful Bill Act**.	• Energy security and resilience

Source: GAO analysis of selected legislation; GAO (icons). | GAO-26-107932

Notes: Dollar amounts are nominal and have not been adjusted for inflation. "Policy goal" is a term used for the purposes of this GAO report. Policy goals were identified through a review of the language of the corresponding legislation. The legislation in the table is not comprehensive, and there may be multiple goals and intentions associated with any piece of legislation or other form of congressional or executive support. We list some associated goals per year as an example, and as they relate to the identified policy goals in this report.

Appendix VII: GAO Contact and Staff Acknowledgments

GAO contact

Karen L. Howard, PhD, Director, Science, Technology Assessment, and Analytics (STAA), at HowardK@gao.gov

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