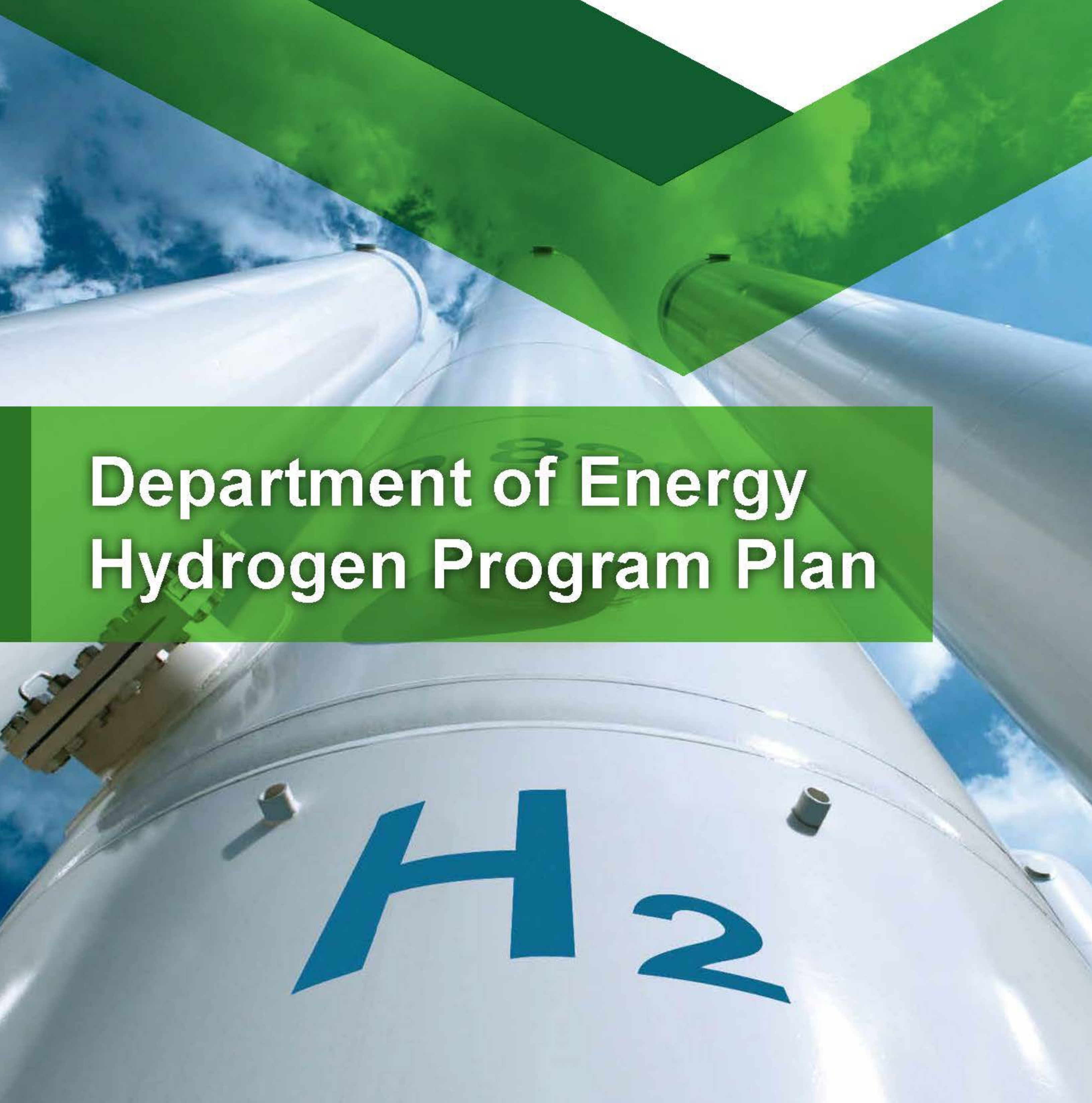
U.S. Department of ENERGY

Department of Energy Hydrogen Program Plan



To Our Stakeholders

Energy is at the nexus of the most pressing challenges of our time—from climate change to threats to energy security and economic resilience and the ongoing need to reduce pollution in our air, waterways, and ecosystems. Thanks to coordinated efforts across government, industry, and civil society, the energy sector has gone a long way toward transitioning to more sustainable technologies and practices. This is especially true with clean hydrogen, which has emerged as an essential tool for addressing challenges across multiple sectors of our economy and has seen accelerating growth and progress in recent years.

Clean hydrogen is part of a comprehensive portfolio of solutions to achieve net-zero-carbon emissions by 2050, as well as create American jobs, energy security, and technology leadership. It has a particularly important role to play in addressing the hardest-to-decarbonize sectors of our economy, while providing cleaner air and economic opportunities for communities across America. It can also support the expansion of low- or zero-carbon electricity by providing a means for long-duration energy storage and offering improved flexibility and revenue for all types of clean power generation—including renewable and nuclear power. Clean hydrogen provides an opportunity to leverage all our nation's energy resources in the transition to a net-zero and sustainable future, including renewables, nuclear power, or fossil and other carbon-based feedstocks (with carbon capture).

Realizing the full potential of clean hydrogen, however, will take a continued commitment to research, development, demonstration, and deployment (RDD&D). While the growth in large-scale deployment projects—such as the Regional Clean Hydrogen Hubs and other industry investments—are essential to achieve scale, grow the supply chain, and reduce costs, their ultimate success will rely in large part on continued advances achieved through coordinated RDD&D efforts. Advancing a coordinated strategy for RDD&D is particularly important—and challenging—for clean hydrogen because it involves virtually every sector of the economy and it can be produced, stored, delivered, and used in such a large number of ways. A successful strategy will need to integrate efforts in renewable, nuclear, and fossil energy—and coordinate across end uses in multiple sectors of the economy.

To meet this challenge, the U.S. Department of Energy (DOE) has developed a *Hydrogen Program Plan*. This plan provides a strategic framework that incorporates RDD&D efforts of the Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy, Office of Electricity, Office of Science, Loan Programs Office, Office of Manufacturing and Energy Supply Chains, Office of Clean Energy Demonstrations, and the Advanced Research Projects Agency – Energy to advance the production, transport, storage, and use of hydrogen across different sectors of the economy.

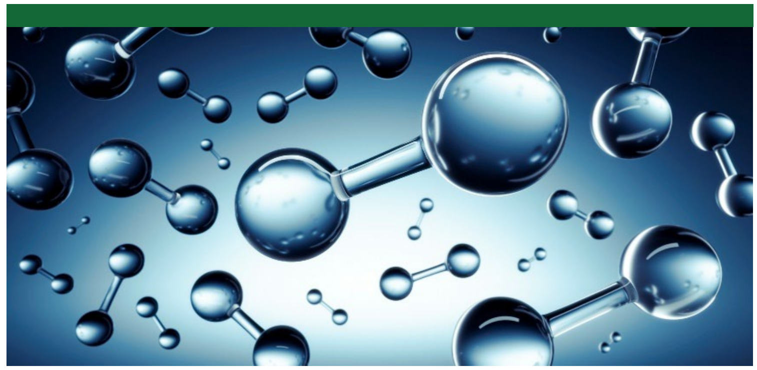
In 2023, several Federal agencies developed the *U.S. National Clean Hydrogen Strategy and Roadmap*, a comprehensive, nationwide framework for accelerating the production, processing, delivery, storage, and use of clean hydrogen. This 2024 update to the *Hydrogen Program Plan* explains how DOE offices collaboratively work to implement the strategies outlined in the *U.S. National Clean Hydrogen Strategy and Roadmap*. This 2024 revision also includes updated supporting data and analysis, a description of the historic Regional Clean Hydrogen Hubs, information about the ambitious DOE-wide goals known as the Hydrogen Shot™, and examples of DOE-wide efforts to establish a strong workforce and environmentally just practices in the transition to a hydrogen economy.

This comprehensive document represents DOE's commitment to develop the technologies that can enable a hydrogen transition in the United States. It also underscores the importance of collaboration both within DOE and with our stakeholders in industry, academia, and the states to achieve that goal.

We hope you will find the *Hydrogen Program Plan* valuable and constructive, and we look forward to working with you to unlock and expand the remarkable potential and benefits of hydrogen.

Jennifer M. Granholm
Secretary of Energy

Executive Summary



The *Department of Energy Hydrogen Program Plan* (the *Plan*) outlines the strategic high-level focus areas of the U.S. Department of Energy's (DOE's) Hydrogen Program (the Program). The term "Hydrogen Program" refers not to any single office within DOE, but rather to the cohesive and coordinated effort of multiple offices that conduct research, development, demonstration, and deployment (RDD&D) activities on hydrogen technologies. The Program includes activities across multiple DOE offices—including the Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy and Carbon Management (FECM), Office of Nuclear Energy (NE), Office of Electricity (OE), Office of Science (SC), Loan Programs Office (LPO), Office of Manufacturing and Energy Supply Chains (MESC), Office of Clean Energy Demonstrations (OCED), and Advanced Research Projects Agency–Energy (ARPA-E). This terminology and the coordinated efforts on hydrogen among relevant DOE offices have been in place since 2004 and provide an inclusive and strategic view of how the department coordinates activities on hydrogen across applications and sectors.

This 2024 version of the *Plan* updates and expands upon previous versions, including the 2020 *Department of Energy Hydrogen Program Plan*,[1] the *Hydrogen Posture Plan*,[2] and *The Department of Energy Hydrogen and Fuel Cells Program Plan*,[3] and provides a coordinated high-level summary of hydrogen-related activities across DOE. The 2006 *Hydrogen Posture Plan* fulfilled the requirement in the Energy Policy Act of 2005 that the Secretary of Energy transmit to Congress a coordinated plan for DOE's hydrogen and fuel cell activities.[4]

This edition of the *Hydrogen Program Plan* reflects DOE's focus on conducting coordinated RDD&D activities to enable the adoption of hydrogen technologies across multiple applications and sectors. It reflects important changes since 2020, including updated supporting data and analysis, a description of the Regional Clean Hydrogen Hubs, information about the ambitious DOE-wide goals known as the Hydrogen Shot, and examples of DOE-wide efforts to establish a strong workforce and community engagement in the transition to a hydrogen economy. This *Plan* describes how offices across DOE collaborate to execute the *U.S. National Clean Hydrogen Strategy and Roadmap*, which sets forth an all-of-government approach to clean hydrogen. While that document provides a roadmap for numerous Federal agencies to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit the United States, this *Hydrogen Program Plan* outlines the specific role of DOE in contributing to the national strategy. The *Plan* includes content from the various plans and documents developed by individual offices within DOE working on hydrogen-related activities, including the Office of Fossil Energy and Carbon Management's *Hydrogen Strategy: Enabling A Low-Carbon Economy*,[5] the Office of Energy Efficiency and Renewable Energy's 2024 *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*,[6]

[1] U.S. Department of Energy. 2020. *Department of Energy Hydrogen Program Plan*. Washington, D.C.: DOE. DOE/EE-2128. hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf?Status=Master.

[2] U.S. Department of Energy and U.S. Department of Transportation. 2006. *Hydrogen Posture Plan. An Integrated Research, Development and Demonstration Plan*. Washington, D.C.: DOE. www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan_dec06.pdf.

[3] U.S. Department of Energy. 2011. The Department of Energy Hydrogen and Fuel Cells Program Plan: An Integrated Strategic Plan for the Research, Development, and Demonstration of Hydrogen and Fuel Cell Technologies. Washington, D.C.: DOE. DOE/EE-0651. www.hydrogen.energy.gov/pdfs/program_plan2011.pdf.

[4] U.S. Congress. 2005. "Energy Policy Act of 2005." P.L. 109-58, 42 U.S. Code § 161534. www.govinfo.gov/content/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf.

[5] Office of Fossil Energy. 2020. *Hydrogen Strategy: Enabling A Low-Carbon Economy*. Washington, D.C.: DOE. www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf.

[6] Office of Energy Efficiency and Renewable Energy. 2024. *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*. Washington, D.C.: DOE. DOE/GO-102024-6266. www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

the cross-office *Pathways to Commercial Liftoff: Clean Hydrogen*[7] and *Pathways to Commercial Liftoff: Advanced Nuclear*,[8] and the Office of Science's *Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies*.[9] Many of these documents are also in the process of updates and revisions and will be posted online. The relationship between these documents is illustrated in Figure ES-1.

Figure ES-1. Relationship between the *U.S. National Clean Hydrogen Strategy and Roadmap*, the *Department of Energy Hydrogen Program Plan*, and DOE office strategic plans and guiding documents

HFTO = Hydrogen and Fuel Cell Technologies Office; BES = Basic Energy Sciences

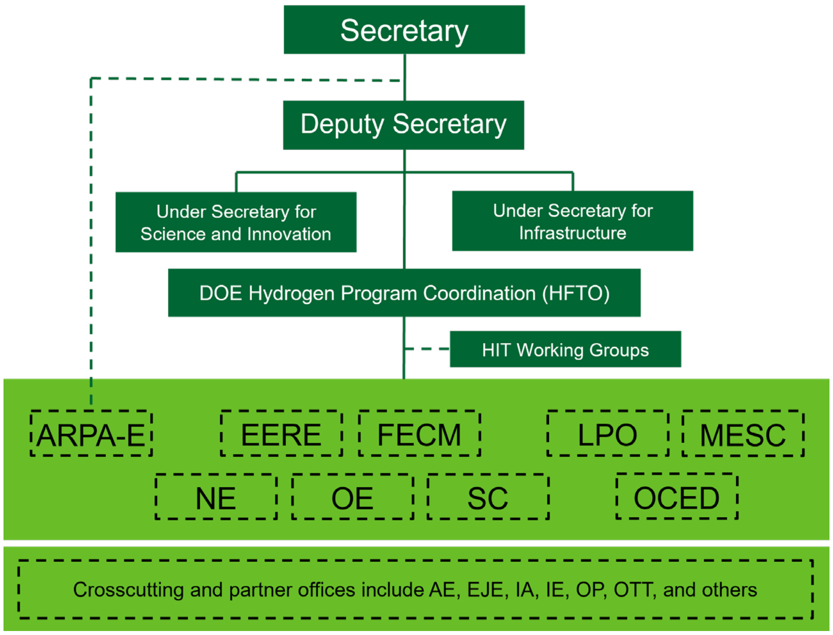


Figure ES-2. DOE Hydrogen Program organizational structure

[7] U.S. Department of Energy. 2023. *Pathways to Commercial Liftoff: Clean Hydrogen*. Washington, D.C.: DOE. liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf. An update to this report is forthcoming.

[8] U.S. Department of Energy. 2023. *Pathways to Commercial Liftoff: Advanced Nuclear*. Washington, D.C.: DOE. liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Advanced-Nuclear-vPUB-0329-Update.pdf.

[9] Morris Bullock and Karren More. 2021. *Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies*. Washington, D.C.: DOE. doi.org/10.2172/1834317.

A key function of this *Plan* is to articulate how DOE offices coordinate to achieve the mission of the DOE Hydrogen Program. Figure ES-2 illustrates the DOE Hydrogen Program organizational structure.[10] Through regular meetings of the DOE Hydrogen and Fuel Cells Joint Strategy Team and sharing research results, technical expertise, and lessons learned in the Hydrogen Interagency Task Force (HIT),[11] offices within DOE have many opportunities to collaborate. Section 4 explains which topic areas individual DOE offices tackle, and which are collaborative efforts.

Through this overarching document, the reader will gain information on the key RDD&D needs to enable the large-scale use of hydrogen and related technologies—such as fuel cells and turbines—in the economy, and how DOE's various offices are addressing those needs. The Hydrogen Program will continue to periodically revise the *Plan*, along with all program office RDD&D plans, to reflect technological progress, programmatic changes, policy decisions, and updates based on stakeholder input and reviews.

[10] Crosscutting and partner offices include the Arctic Energy Office (AE), Office of Energy Justice and Equity (EJE), Office of International Affairs (IA), Office of Indian Energy Policy and Programs (IE), Office of Policy (OP), and Office of Technology Transitions (OTT).
[11] The Hydrogen and Fuel Cell Technologies Office has led this group for well over a decade, consistent with Section 806 of the Energy Policy Act of 2005, 2 U.S.C. §16155, which directs DOE to lead a Hydrogen and Fuel Cell Interagency Task Force.

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1 Introduction

The U.S. Department of Energy (DOE) *Hydrogen Program Plan* (the *Plan*) communicates DOE's overarching, cross-office strategic plan to accelerate research, development, demonstration, and deployment (RDD&D) of hydrogen and related technologies in the United States. The *Plan* provides an overview of core technology areas, challenges, and RDD&D thrusts that DOE is pursuing to address these challenges through an integrated DOE Hydrogen Program (the Program). The Program includes activities across multiple DOE offices—including the Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy and Carbon Management (FECM), Office of Nuclear Energy (NE), Office of Electricity (OE), Office of Science (SC), Loan Programs Office (LPO), Office of Manufacturing and Energy Supply Chains (MESC), Office of Clean Energy Demonstrations (OCED), and Advanced Research Projects Agency–Energy (ARPA-E). While each office has its own planning documents, including program plans and multiyear RDD&D plans, this overarching document provides a high-level framework summarizing activities relevant to all offices and describes how offices across DOE will execute the *U.S. National Clean Hydrogen Strategy and Roadmap*, which sets forth an all-of-government approach to clean hydrogen. This *Plan* updates the previous version, which built upon preceding strategic and planning documents including the 2020 *Department of Energy Hydrogen Program Plan*.[12] Based on extensive stakeholder input and progress over the last two decades, the *Plan* serves as a guiding summary of focus areas and the path forward across all relevant DOE offices. In addition to this overarching DOE-wide plan, each office within DOE has its own detailed technical plans and strategies relevant to their mission areas.[13]

The 2024 version of the *Plan* updates and expands upon previous versions, including the 2020 *Department of Energy Hydrogen Program Plan*, the *Hydrogen Posture Plan*,[14] and *The Department of Energy Hydrogen and Fuel Cells Program Plan*,[15] and provides a coordinated high-level summary of hydrogen-related activities across DOE. The 2006 *Hydrogen Posture Plan* fulfilled the requirement in the Energy Policy Act of 2005 that the Secretary of Energy transmit to Congress a coordinated plan for DOE's hydrogen and fuel cell activities.[16]

This *Plan* builds upon aspects in the individual DOE office plans and documents, FECM's *Hydrogen Strategy: Enabling A Low-Carbon Economy*,[17] EERE's 2024 *Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan*,[18] the cross-office *Pathways to Commercial Liftoff: Clean Hydrogen*[19] and *Pathways to Commercial Liftoff: Advanced Nuclear*,[20] and SC's *Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies*.[21] Many of these documents are also in the process of updates and revisions and will be posted online and incorporated into future versions of this *Plan*.

Clean hydrogen is part of a comprehensive energy portfolio that can enable energy security and resiliency and provide economic value and environmental benefits for diverse applications across multiple sectors. Clean hydrogen, which is produced with low or zero emissions, can be derived from a variety of domestic energy sources, including renewables; fossil fuels with carbon capture, utilization, and storage (CCUS); and nuclear power. Diverse, sustainable, and abundant domestic resources are essential for the nation to (1) provide for a variety of end uses and a range of energy needs, (2) reduce dependency on single or limited resources, (3) retain energy independence and expand opportunities for net exports, and (4) be prepared for future scenarios where resources,

[12] U.S. Department of Energy. 2020. Department of Energy Hydrogen Program Plan.
[13] U.S. Department of Energy. 2024. "Program Areas." Accessed Oct. 1, 2024. www.hydrogen.energy.gov/program_areas.html.
[14] U.S. Department of Energy and U.S. Department of Transportation. 2006. *Hydrogen Posture Plan*.
[15] U.S. Department of Energy. 2011. The Department of Energy Hydrogen and Fuel Cells Program Plan.
[16] U.S. Congress. 2005. "Energy Policy Act of 2005."
[17] Office of Fossil Energy. 2020. *Hydrogen Strategy*.
[18] Office of Energy Efficiency and Renewable Energy. 2024. Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan.
[19] U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Clean Hydrogen. An update to this report is forthcoming.
[20] U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Advanced Nuclear.
[21] Bullock and More. 2021. Basic Energy Sciences Roundtable.

end-use needs, and constraints may change significantly. Flexibility is a key asset, and hydrogen provides that opportunity.

The United States has been at the forefront of hydrogen and related technology RDD&D, from its inception in the space program to enabling technology commercialization in transportation, stationary power, and portable power applications. The origins of DOE's program in hydrogen technologies date back to the establishment of DOE itself in the mid-1970s, when energy security and dependence on foreign oil were major concerns. Over the years, DOE established robust RDD&D activities on hydrogen and related technology aligned with a number of statutory authorities, including the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 and the Energy Policy Act of 2005.[22,23]

Hydrogen Overview—Benefits and Uses

Given its potential to help address the climate crisis, enhance energy security and resilience, and create economic value, interest in producing and using clean hydrogen is intensifying both in the United States and abroad. Clean hydrogen is a key part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future. The United States is stepping up to accelerate progress through historic investments in clean hydrogen production, midstream infrastructure, and strategically targeted RDD&D in this critical technology.

Hydrogen is the most abundant element in the universe; however, it is rarely found in its elemental form on Earth. It must be produced from a hydrogen-containing feedstock (e.g., water, biomass, fossil fuels, waste materials) using an energy source. Once hydrogen is produced, it can be used to store, move, and deliver low- or no-carbon energy to where it is needed. Hydrogen can be stored as a liquid, gas, or chemical compound, and is converted to energy via traditional combustion methods (in engines, furnaces, or gas turbines), through electrochemical processes (in fuel cells), and through hybrid approaches such as integrated combined-cycle gasification and fuel cell systems. It is also used as a feedstock or fuel in a number of industries, including petroleum refining, ammonia production, food and pharmaceutical production, and metals manufacturing. Hydrogen can be produced in large, centralized production facilities or in smaller, distributed production facilities, and can be transported via truck, pipeline, tanker, or other means.

Key Benefits of Hydrogen

- Hydrogen can be produced from diverse domestic resources for use in multiple sectors, or for export.
- Hydrogen has the highest energy content by weight of all common fuels—3 times higher than gasoline—and is a critical feedstock for the entire chemicals industry, including for liquid fuels.
- Hydrogen, along with fuel cells or combustion-based technologies, can enable zero or near-zero emissions in transportation, stationary or remote power, and portable power applications.
- Hydrogen can be used for gigawatt-hours of energy storage and as a "responsive load" on the grid to enable grid stability, increasing the utilization of power generators, including nuclear, coal, natural gas, and renewables.
- Hydrogen can be used to decarbonize a variety of domestic industries, such as the manufacturing of steel, cement, ammonia, and other chemicals.

Hydrogen, as a versatile energy carrier and chemical feedstock, offers advantages that unite all of our nation's energy resources—renewables, nuclear, and fossil fuels—and enables innovations in energy production and end uses that can help decarbonize three of the most energy-intensive sectors of our economy: transportation, electricity generation, and manufacturing.

As shown in Figure 1, there are a wide range of applications where the use of hydrogen is either growing or has the potential for significant future demand. These diverse applications highlight the scale of the technical

[22] U.S. Congress. 1990. "Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990." P.L. 101-566, Nov. 15, 1990. www.congress.gov/bill/101st-congress/senate-bill/639.
[23] U.S. Congress. 2005. "Energy Policy Act of 2005."

potential for hydrogen and related technologies. This potential is also being recognized worldwide, with investments by government and industry ramping up in many countries, including the United States. For example, the U.S. Government announced $8 billion for the Regional Clean Hydrogen Hubs Program (H2Hubs), which will kick-start a national network of clean hydrogen producers, consumers, and connective infrastructure while supporting the production, storage, delivery, and end use of clean hydrogen.[24] Additional information on H2Hubs can be found later in this document. The H2Hubs will catalyze billions of dollars in private investment—exemplifying a private sector-led, government-enabled strategy. Additionally, DOE has issued loans and conditional loan guarantees to several large-scale clean hydrogen production projects, continuing to spur public and private investment in clean hydrogen.

Hydrogen feedstocks are expected to represent an $80–$150 billion domestic market by 2050,[25,26] and annual shipments of fuel cells have increased 15-fold since 2015, now at more than 1 GW.[27] The DOE *Pathways to Commercial Liftoff: Clean Hydrogen* report concludes that by 2030, the hydrogen economy could create approximately 100,000 net new direct and indirect jobs.

	Industrial feedstocks	Transportation	Power generation & energy storage	Buildings and hydrogen blending
Existing demands at limited current scales	• Oil refining • Ammonia • Methanol • Other (e.g. food, chemicals)	• Forklifts and other material-handling equipment • Buses • Light-duty vehicles	• Distributed generation: primary and backup power • Renewable grid integration with storage and other ancillary services	• Low-percentage hydrogen blending in limited regions
Emerging demands and potential new opportunities	• Steel and cement manufacturing • Industrial heat • Bio/synthetic fuels and products using hydrogen	• Hydrogen / biofuels using hydrogen for medium- and heavy-duty applications: o Trucks o Rail o Maritime o Aviation (e.g., sustainable aviation fuels) o Off-road equipment (mining, construction, agriculture)	• Long-duration energy storage • Hydrogen low NOx combustion • Direct/reversible fuel cells • Nuclear/hydrogen hybrids • Fossil/waste/biomass hydrogen hybrids with CCUS	• Mid- to high-percentage hydrogen blending in certain regions with limited alternatives • Building or district heating, including fuel cells and combined heat and power, for hard-to-electrify or limited options

Figure 1. Existing and emerging demands for hydrogen

Progress and Needs

Over the past 40 years, hydrogen and related technologies, such as fuel cells and turbines, have transitioned from highly specialized applications to commercially available products. Thousands of fuel cells are already in use in passenger and commercial vehicles, forklifts, and stationary and backup power units throughout the United States. The number of retail hydrogen fueling stations has grown to approximately 50 over the past few years, and more than 150 when including infrastructure for niche markets in material handling. In power generation, advances have led to commercialization of large-frame turbines that can fire hydrogen/natural gas blends. Much

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[24] U.S. Department of Energy. 2023. "Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogen Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide." Oct. 13, 2023. www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving.

[25] U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Clean Hydrogen. An update to this report is forthcoming.

[26] Hydrogen Council. 2017. *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition*. hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf.

[27] E4tech. 2019. *The Fuel Cell Industry Review 2019*. www.erm.com/globalassets/documents/fuel-cell-industry-review/thefuelcellindustryreview2019.pdf.

of this transition has been enabled by RDD&D advances from DOE. Over the past 20 years, DOE has invested more than $12 billion in a number of hydrogen and related areas, including hydrogen production from diverse domestic sources, hydrogen delivery and storage, and conversion technologies including fuel cells and turbines. These research efforts, in collaboration with industry, have resulted in a number of successes such as advanced production systems capable of producing low-carbon hydrogen for less than $2/kg with carbon capture and storage.[28] DOE-funded RDD&D has also reduced the cost of transportation fuel cells by 60%, quadrupled durability, and resulted in more than 1,100 U.S. patents issued and more than 30 commercial technologies on the market.[29]

The key technical challenges for hydrogen and related technologies are cost, durability, reliability, and performance, as well as the lack of established hydrogen delivery and storage infrastructure. To achieve widespread commercialization, hydrogen utilization technologies must enter larger markets and be able to compete with incumbent technologies in terms of life cycle cost, performance, durability, and environmental impact. Nontechnical barriers also need to be addressed. These include developing and harmonizing codes and standards, establishing high-volume offtake agreements with creditworthy customers, fostering best practices for safety, and developing a robust supply chain and workforce. Additionally, two-way community engagement and education will be essential for developing a robust hydrogen economy.

The DOE Hydrogen Program is working to meet the needs and overcome the challenges in each of the core technical and institutional areas, as shown in Table 1.

Table 1. The Hydrogen Energy System and Its Needs and Challenges

Key Aspects of the Hydrogen Energy System	Needs and Challenges
PRODUCTION: Hydrogen can be produced from diverse domestic resources—including fossil fuels, nuclear energy, and renewables (wind, solar, geothermal, biomass, and waste, including plastics). The primary pathways for producing hydrogen are through thermochemical processes such as reforming, gasification, and pyrolysis, and through electrolysis via water splitting. Hydrogen also offers the options of large-scale centralized production or distributed production at small facilities, close to or at the point of use.	• Lower-cost, more efficient, and more durable electrolyzers. • Advanced designs for reforming, gasification, and pyrolysis. • Scale-up of hydrogen production techniques from renewable, fossil, and nuclear energy resources, including hybrid and fuel-flexible approaches. • Advanced and innovative technologies to lower the cost and increase efficiency of producing hydrogen from water, fossil fuels, biomass, and waste. • Low-cost and environmentally sound CCUS technologies.
DELIVERY: Hydrogen can be transported and dispensed either as pure hydrogen or as part of a chemical carrier via several different pathways: distributed in pipelines, transported in high-pressure tanks, or carried as a liquid via tanker truck. Large volumes of hydrogen can also be transported by rail or ships. End-use applications could have varying needs for flow rates, purity, and cost, imposing different requirements on the refueling infrastructure.	• Lower-cost and more reliable systems for distributing and dispensing hydrogen. • Advanced technologies and concepts for hydrogen distribution, including liquefaction and material-based chemical carriers. • Rights-of-way, permitting, and reduced investment risk of deploying delivery infrastructure.
STORAGE: Hydrogen may need to be stored prior to use—either in bulk, at the site of production, during the delivery process, or at the point of use—and this can be accomplished via (1) physical storage, which includes high-pressure tanks for compressed gaseous hydrogen and cryogenic tanks for liquid hydrogen; or (2) material-based processes that incorporate hydrogen in chemical compounds, with the potential for higher capacities at ambient temperature and pressure. Additional approaches—such as	• Lower-cost hydrogen storage systems. • Higher storage capacity, with reduced weight and volume. • Large-scale storage, including on-site bulk emergency supply and in geologic formations. • Optimized storage strategies for co-locating stored hydrogen with end-use applications to meet

[28] S. McNaul, C. White, R. Wallace, et al. 2023. *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*. Pittsburgh, PA: National Energy Technology Laboratory. doi.org/10.2172/2228279.
[29] Patents and technologies resulting from RD&D funded by the EERE Hydrogen and Fuel Cell Technologies Office; Lindsay Steele. 2020. "2019 Patent Analysis for the U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office." PNNL-SA-156721. www.energy.gov/sites/prod/files/2020/10/f79/hfto-2019-patent-analysis.pdf.

Key Aspects of the Hydrogen Energy System	Needs and Challenges
geologic storage—may be needed for large-scale, long-term hydrogen storage.	throughput and dynamic response requirements and reduce investment cost.
CONVERSION: To be useful, the energy carried by hydrogen must be converted into a different form, such as electricity or heat, and this can be accomplished through electrochemical conversion using fuel cells, or via combustion using turbines or reciprocating engines. Hybrid systems, such as natural gas/other fuel combined-cycle fuel cell systems offer high efficiencies and reduced emissions compared with conventional technologies.	• Lower-cost, more durable, and more reliable fuel cells that can be mass produced. • Turbines that can operate on high concentrations of hydrogen or pure hydrogen. • Development and demonstration of large-scale hybrid systems.
END-USE APPLICATIONS AND INTEGRATED ENERGY SYSTEMS: Hydrogen can be used in diverse applications across multiple sectors. It can provide value directly to end-use applications (e.g., heavy-duty transportation, stationary power, industrial and chemical applications) and as an enabler of integrated energy systems, where it can improve the economics and performance of existing and emerging electric power generators.	• Systems integration, testing, and validation to identify and address the challenges unique to each application. • Demonstration of end-use applications, including steel manufacturing, ammonia production, and techniques for producing synthetic fuels from hydrogen and carbon dioxide. • Demonstration of successful grid integration to validate hydrogen energy storage and grid services at scale.
MANUFACTURING AND SUPPLY CHAIN: Advanced manufacturing processes and a robust supply chain for hydrogen, fuel cell, and hydrogen turbine technologies can enable cost reductions and commercial-scale production.	• Standardized manufacturing processes, quality control, and optimized design for manufacturing. • Additive and automated manufacturing processes. • Design for recyclability and waste reduction.
SAFETY, CODES, AND STANDARDS: Technically sound codes and standards could provide an essential basis for the safe and consistent deployment and commercialization of hydrogen and related technologies. Along with widely shared safety information and best practices, they could also improve confidence in the commercial viability of the technologies among all stakeholders, which can further accelerate adoption and encourage investment.	• Appropriate, uniform codes and standards to address all end-use applications, including for combustion applications (e.g., turbines) and fuel cells (e.g., high throughput fueling for heavy-duty applications, including trucks, marine, and rail). • Improved safety information and sharing of best practices and lessons learned.
EDUCATION, WORKFORCE, AND ENVIRONMENTAL JUSTICE: A highly skilled workforce can effectively respond to growth in hydrogen-related industries and can support and sustain an environmentally just, national competitive advantage in this advanced energy technology field. Community engagement, increased transparency, and two-way communication can build confidence in the safe use of hydrogen as an energy carrier among key constituencies, including investors, policymakers, the general public, and those communities most affected by the introduction of hydrogen-related industries.	• Educational resources and training programs for diverse stakeholders, including first responders, code officials, and technicians (e.g., on operations, maintenance, and handling of hydrogen and related technologies). • Increased community outreach, including listening to and increasing transparency with various impacted groups such as Tribes and community members impacted by the introduction of hydrogen-related industries. • Resources allocated to addressing the concerns of communities could increase public support for hydrogen technologies. • Access to accurate, objective information about hydrogen and related technologies.

Over the years, a number of technology options have been discovered and developed to meet key needs in each technical area, and substantial progress has been made in many of them. As shown in Figure 2, these options span the full spectrum of near- to longer-term large-scale market adoption. The expected time frame for adoption is based both on technology maturity and expected demand. Some technologies may be technologically mature but have not yet developed sufficient demand for widespread adoption.

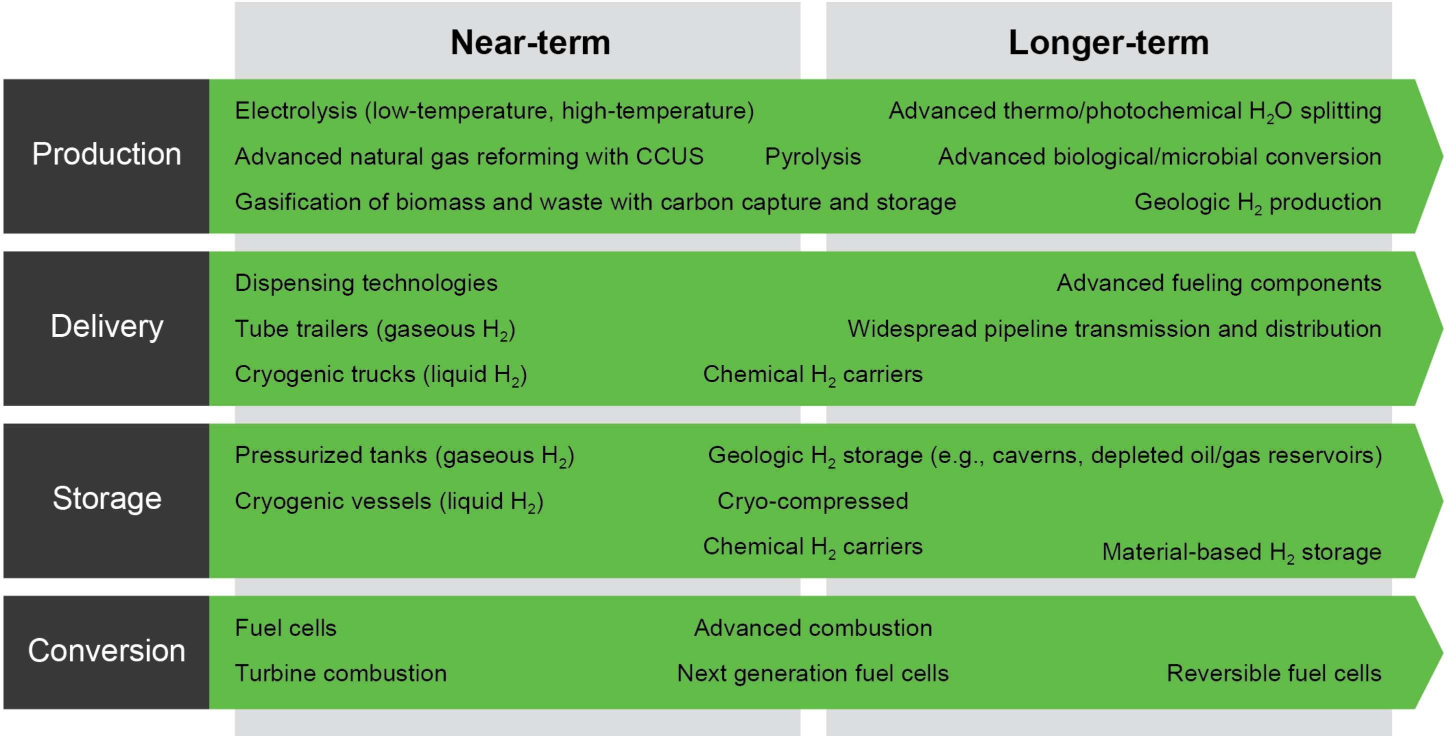


Figure 2. Key hydrogen technology options

2 DOE Hydrogen Program

Program Mission

Vision: Affordable, clean hydrogen for a net-zero-carbon future and a sustainable, resilient, and equitable economy

The DOE Hydrogen Program focuses on RDD&D of technologies for clean hydrogen production through end use and addresses institutional and market barriers to enable adoption across multiple applications and sectors.

To accomplish this mission, the Program works in partnership with industry, academia, national laboratories, Federal and international agencies, environmental justice communities, and other stakeholders to:

- Overcome technical barriers through basic and applied research and development (R&D).
- Integrate, demonstrate, and validate "first-of-a-kind" hydrogen and related technologies.
- Accelerate the transition of innovations and technologies to the private sector.
- Address institutional issues including safety concerns, environmental injustices, education and workforce development gaps, and the development of codes and standards.
- Identify, implement, and refine appropriate strategies for Federal programs to catalyze a sustainable market and concomitant benefits to the economy, the environment, all members of the public, and energy security.

In addition to participation from EERE, FECM, NE, OE, SC, LPO, MESC, OCED, and ARPA-E, the Hydrogen Program also coordinates with other DOE offices, including the Arctic Energy Office, Office of Energy Justice and Equity, Office of International Affairs, Office of Indian Energy Policy and Programs, Office of Policy, and Office of Technology Transitions. There are also several crosscutting DOE efforts, such as the DOE Hydrogen and Fuel Cells Joint Strategy Team and the Hydrogen Shot (described in more detail in Section 4). Each of these offices and initiatives manages hydrogen technology activities related to their missions. EERE, FECM, and NE focus their RDD&D activities on their respective energy sources, feedstocks, and target applications. These activities are coordinated to achieve a cohesive and strategically managed effort. More information on Hydrogen Program execution and collaboration is provided in Section 4.

Hydrogen at Scale—A Guiding Framework

H2@Scale is a DOE initiative that provides an overarching vision for how hydrogen can enable energy pathways across applications and sectors in an increasingly interconnected energy system.[30] The H2@Scale concept, shown in Figure 3, is based on hydrogen's potential to meet existing and emerging market demands across multiple sectors. It envisions how innovations to produce, store, transport, and utilize hydrogen can help realize that potential and achieve scale to drive revenue opportunities and reduce costs.

[30] Hydrogen and Fuel Cell Technologies Office. 2024. "H2@Scale." Accessed Oct. 2, 2024. www.energy.gov/eere/fuelcells/h2-scale.

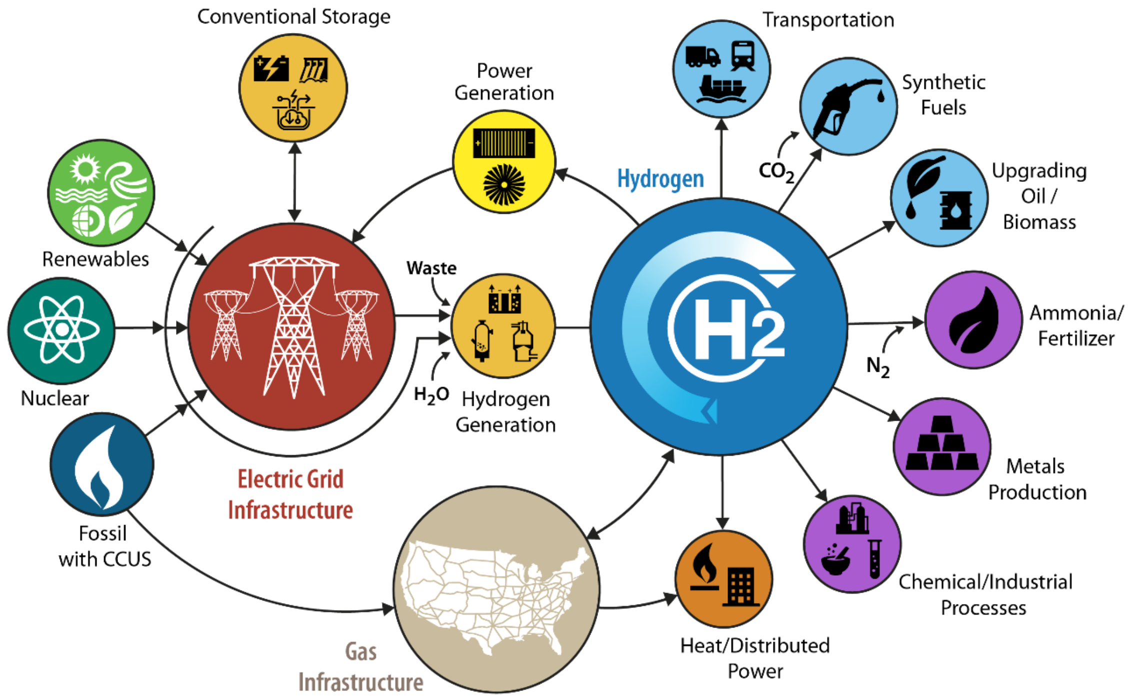


Figure 3. Conceptual H2@Scale energy system[31]

Today, the primary demand for hydrogen is as a chemical feedstock in petroleum refining and ammonia production, with smaller amounts being used in other industrial applications such as methanol production. Approximately 10 million metric tons (MMT) of hydrogen are currently produced in the United States each year for these end uses, mostly from natural gas. In the H2@Scale vision, hydrogen's versatility as a both a chemical feedstock and an energy carrier could be harnessed to serve expanded end uses. Emerging market opportunities include the use of hydrogen for multiple transportation applications (e.g., in fuel cell electric vehicles—particularly heavy-duty applications—as a feedstock for synthetic fuels, and to upgrade petroleum and biofuels); as a feedstock for industry (e.g., in steel and cement manufacturing); for heat in industrial systems and buildings; for power generation (for large-scale power, off-grid distributed power, and backup or emergency power); and for energy storage. Hybrid energy systems, which integrate energy generation, storage, and/or conversion technologies to optimize the overall value of the energy generated, are another promising market opportunity, as discussed in the Applications section of Section 3. For example, the integration of hydrogen production technologies with utility-scale power generation plants is a concept receiving increased interest due to its potential to improve profitability of these plants while supporting grid resiliency.[32]

The ultimate goal of H2@Scale is for hydrogen to be affordably produced and delivered utilizing several feedstocks, processing methods, and delivery options at a variety of scales ranging from large, central production to small, local production, depending on what is most practical from an economic and logistical perspective for a given location and level of market demand. To better understand and develop the potential for hydrogen production, demand, and utilization in the United States, the Hydrogen Program conducts coordinated, comprehensive modeling and analysis efforts, which examine the options available, current and potential costs, energy efficiencies, and environmental effects of these options, as well as trade-offs between them. Results from

[31] Hydrogen and Fuel Cell Technologies Office. 2024. "H2@Scale." Schematic developed over 3 years of stakeholder engagement with national labs and industry; an illustrative example depicting key applications and how hydrogen may be put on par with today's electric and natural gas "grids."

[32] A relevant example is a wind farm or nuclear power plant that produces hydrogen from surplus electricity (via electrolysis) and then either sells or uses the hydrogen for other purposes or reconverts it to electricity (via a fuel cell or turbine) at times of higher demand.

these analyses are used to help guide RDD&D priorities and set program goals, including potential regional focus areas for hydrogen production and utilization, as well as the most viable end-use applications.

Deployments of clean hydrogen to decarbonize industry, transportation, and the power grid could lead to hydrogen demand of 10 MMT/year by 2030, about 20 MMT by 2040, and about 50 MMT by 2050.

Recent H2@Scale modeling and analysis efforts conducted by DOE's National Labs have characterized U.S. hydrogen production and demand potential over the next 30 years. Figure 4 depicts scenarios for the demand expected in each sector if clean hydrogen is available (produced, delivered, and dispensed) at the threshold prices shown. For instance, approximately $5/kg for hydrogen produced, delivered, compressed, and dispensed would pave the way for early adopters in the fuel cell truck markets. At approximately $4/kg, scenario analyses have shown that 10%–14% of all medium- and heavy-duty fuel cell trucks would demand about 5–8 MMT/year of hydrogen. The lighter shaded bars represent a more optimistic demand scenario for each market shown. Given the uncertainty in other variables such as fuel cell cost, efficiency, durability, onboard hydrogen storage, and infrastructure, as well as the cost of incumbent fuels and technologies, analyses will continue to be refined. However, these results indicate large potential volumes for clean hydrogen demand, assuming DOE targets for clean hydrogen costs are met. See the *U.S. National Clean Hydrogen Strategy and Roadmap* and *Pathways to Commercial Liftoff: Clean Hydrogen* for more information.[33]

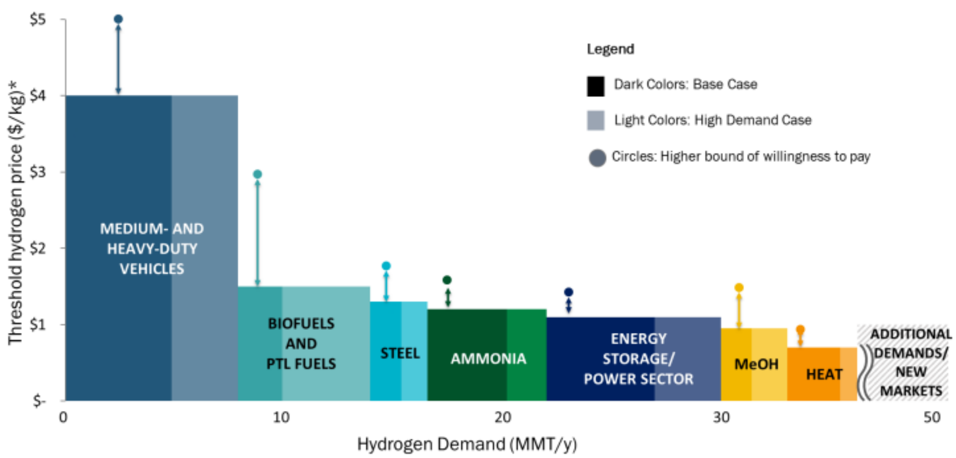


Figure 4. Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost

The Hydrogen Program has also determined the availability of domestic resources for hydrogen production across the country, along with associated infrastructure that can be leveraged for hydrogen services. Figures below depict the locations of resources and infrastructure throughout the United States, along with the locations where renewables, fossil resources, and nuclear power can be leveraged for clean hydrogen production. The nation's energy resources are geographically widespread; renewable, fossil, and nuclear resources are each independently sufficient to support a significant increase, specifically in domestic clean hydrogen production and consumption.[34]

Today, most of the approximately 10 MMT of hydrogen used annually in the United States is produced through steam methane reforming (SMR) of natural gas, which results in associated carbon dioxide (CO_2) emissions. Figure 5 illustrates where most of the current hydrogen production facilities are located, along with the supporting

[33] Sunita Satyapal, Neha Rustagi, Tomas Green, Marc Melaina, Michael Penev, and Mariya Koleva. 2023. *U.S. National Clean Hydrogen Strategy and Roadmap*. Washington, D.C.: DOE. www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5.

[34] E. Connelly, M. Penev, A. Milbrandt, B. Roberts, N. Gilroy, and M. Melaina. 2020. *Resource Assessment for Hydrogen Production*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-77198. www.nrel.gov/docs/fy20osti/77198.pdf.

pipeline infrastructure for both natural gas and hydrogen. Carbon capture technologies have been demonstrated at some of the natural gas reforming facilities.

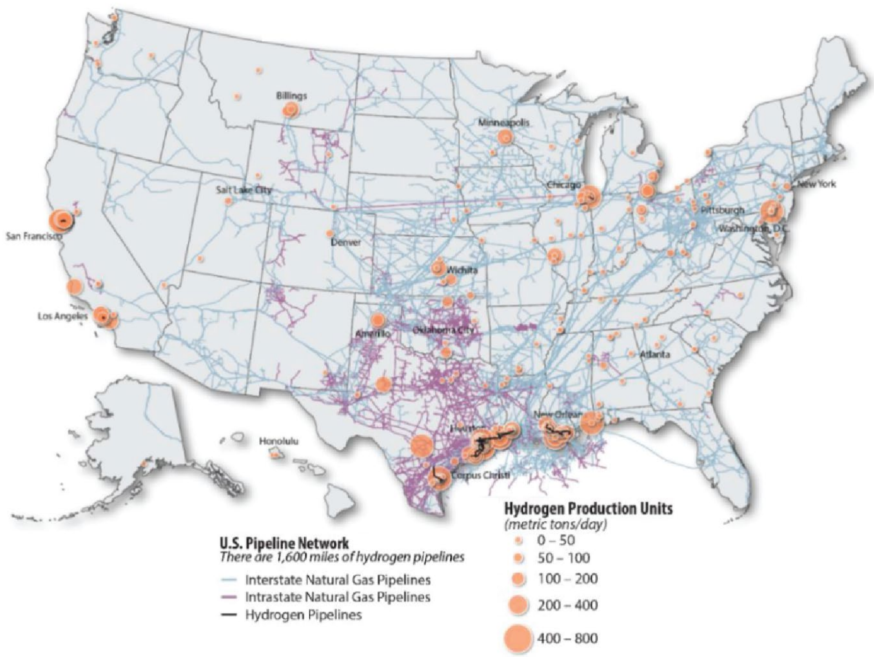


Figure 5. Hydrogen production units and pipelines for hydrogen and natural gas in the United States[35]

Emerging options for clean hydrogen produced with significantly reduced CO_2 emissions relative to incumbent technologies include coupling carbon capture and utilization or storge with SMR and autothermal reforming of natural gas, as well as methane pyrolysis, which produces hydrogen with a solid carbon byproduct. Hydrogen produced by water electrolysis using electricity from renewables and/or nuclear power results in near-zero CO_2 emissions. Figure 6 shows a map of announced clean hydrogen production projects as of January 2024, illustrating the diversity of the growing options.[36] Circles and triangles represent locations of announced clean hydrogen projects in addition to the H2Hubs and are colored by production pathway and sized by announced capacity, where available. Where only state-level location is available, circles are placed in the center of the state containing the hydrogen project.

[35] Data source: IHS Markit. 2018. *Chemical Economics Handbook: Hydrogen*. Natural gas pipeline data extracted from ABB's Velocity Suite (2016).

[36] Note that there is a rapidly expanding number of clean hydrogen projects in planning and under construction; for the most up-to-date numbers, refer to www.hydrogen.energy.gov/library/program-records.

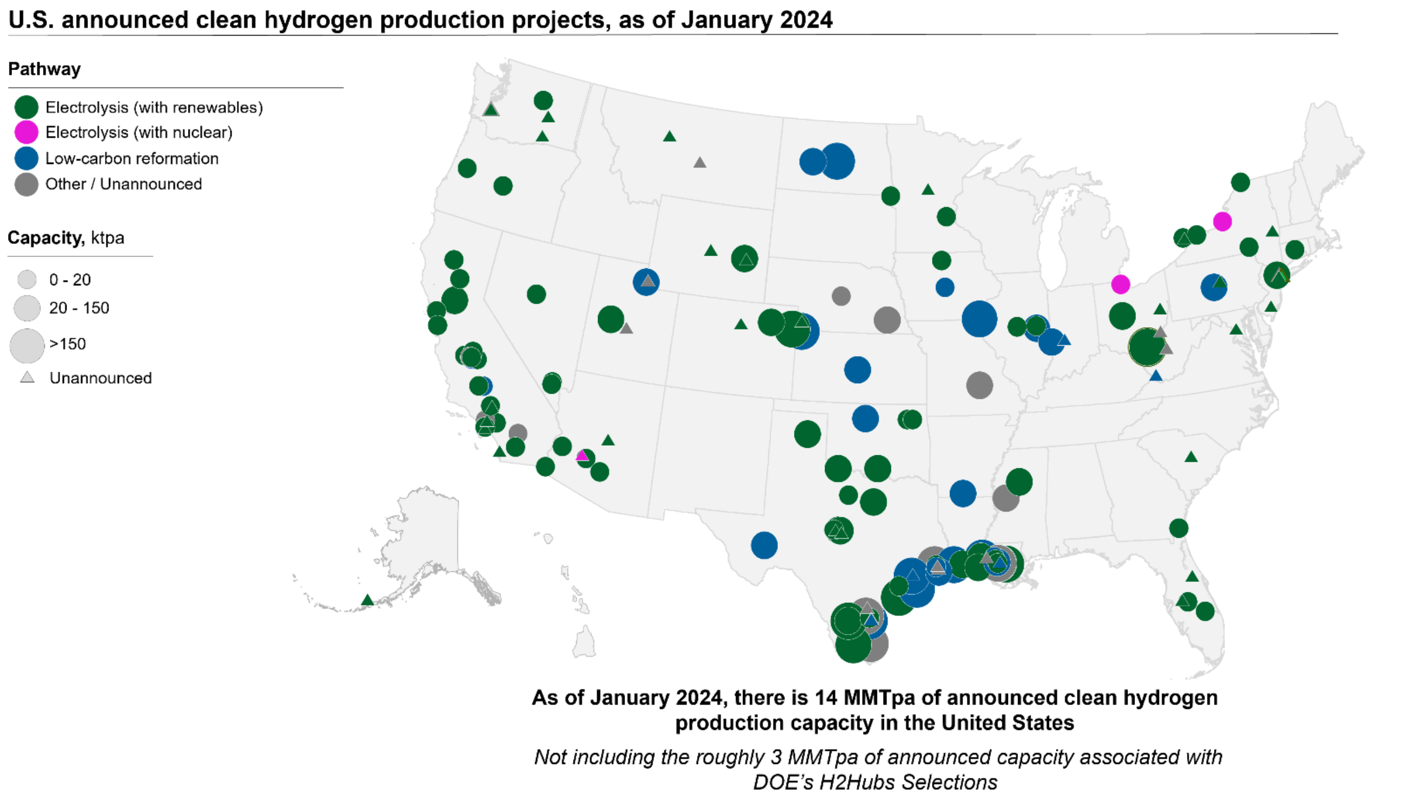


Figure 6. Clean hydrogen production projects announced as of January 2024[37]

Electrolyzer capacity has been growing significantly in recent years across the United States. Figure 7 illustrates the location of the current planned and/or installed electrolyzer facilities, with a total capacity of 4.5 GW as of 2024. This includes 1 GW of capacity added since 2023 alone, with continued expansion expected.[38]

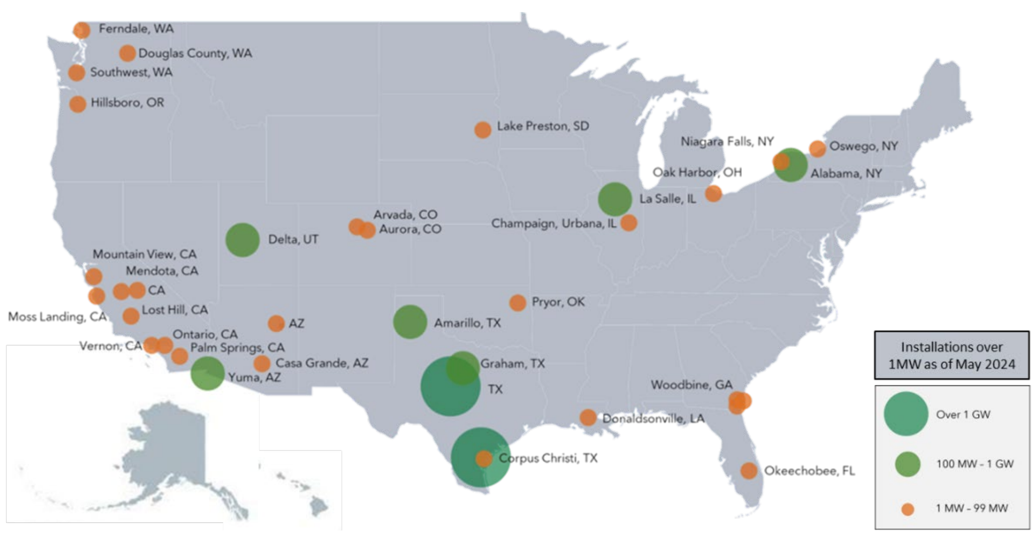


Figure 7. Planned and installed electrolyzer capacity in the United States as of 2024.[39]
Includes proton exchange membrane, solid oxide electrolyzer cells, and alkaline electrolyzers

[37] Figure adapted from DOE's ongoing *Pathways to Commercial Liftoff* efforts, January 2024. An update to this report is forthcoming. Projects without at least state-level location information are excluded from the map and projects with only a state-level location are placed at the respective state's center on the map.

[38] Note that there is a rapidly expanding number of planned and installed electrolyzer facilities; for the most up-to-date numbers, refer to www.hydrogen.energy.gov/library/program-records.

[39] M. Hubert and V. Arjona. 2024. "Electrolyzer Installations in the United States." DOE Hydrogen Program Record 24001. www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24001-electrolyzer-installations-united-states.pdf?sfvrsn=43ae10f_1. Note that there are numerous installations in multiple states (including Hawaii and Alaska) that are currently below 1 MW; refer to DOE Hydrogen Program Record 24001 for a complete listing.

Many of the planned and installed electrolyzer facilities are being co-located with regionally specific resources for clean electricity generation, such as wind, solar, nuclear, and hydropower. Figure 8 summarizes analysis evaluating the clean hydrogen production potential across the United States from electrolysis leveraging these clean electricity resources including the current nuclear fleet and renewable resources. Two additional advanced reactors will be deployed in Kemmerer, Wyoming, near a retired coal plant, and Seadrift, Texas. An additional 200 GW of nuclear capacity is targeted by 2050, but the locations are yet to be determined. A more detailed breakdown of specific renewable energy resources that could be leveraged to produce hydrogen is shown in Figure 9.

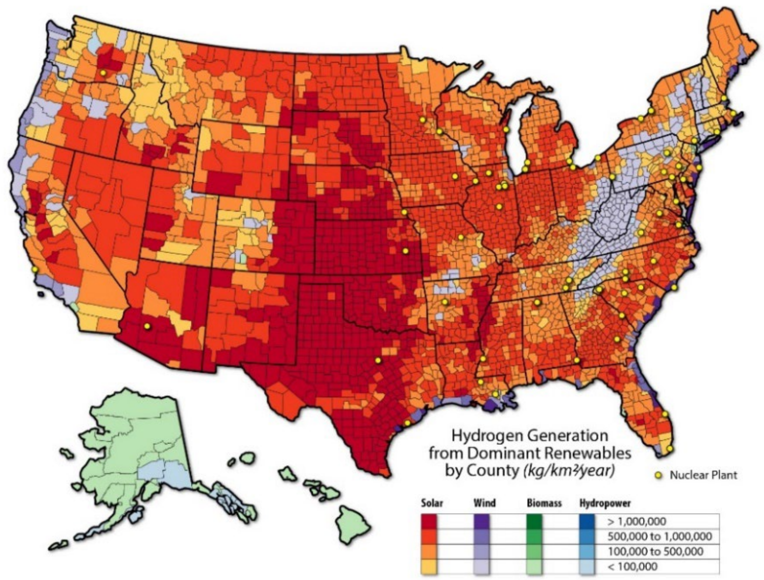
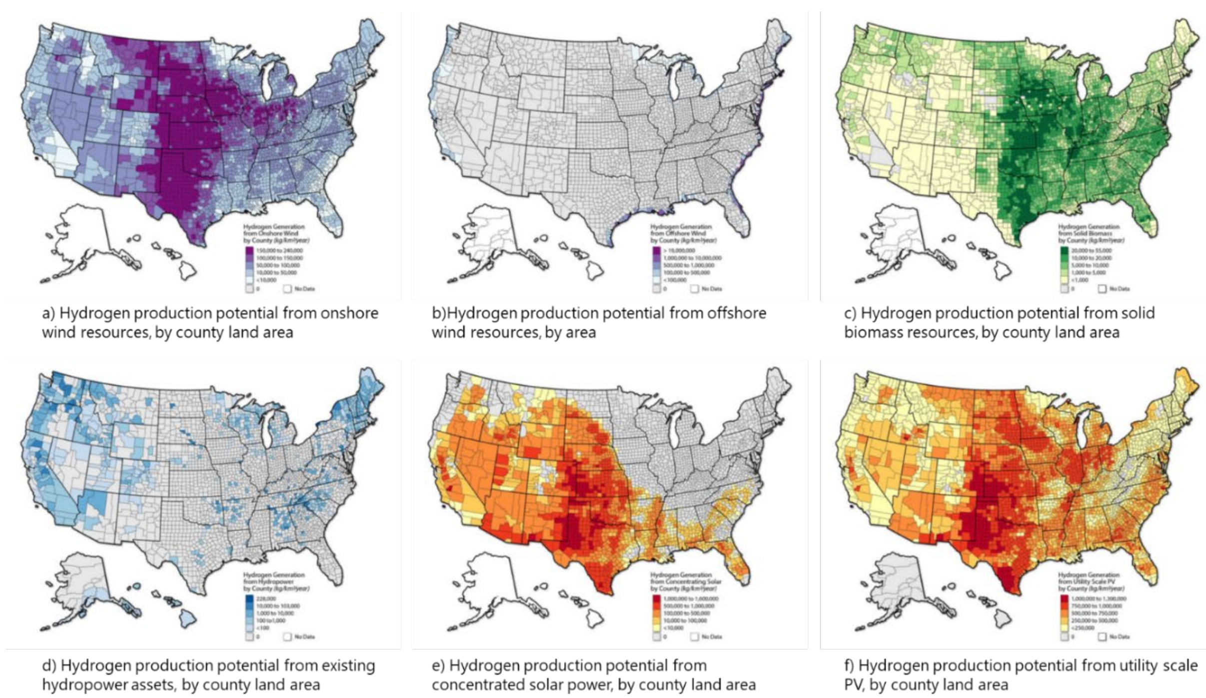


Figure 8. Hydrogen production potential leveraging diverse domestic clean power sources across the United States[40]



a) Hydrogen production potential from onshore wind resources, by county land area

b)Hydrogen production potential from offshore wind resources, by area

c) Hydrogen production potential from solid biomass resources, by county land area

d) Hydrogen production potential from existing hydropower assets, by county land area

e) Hydrogen production potential from concentrated solar power, by county land area

f) Hydrogen production potential from utility scale PV, by county land area

Figure 9. Production potential for clean hydrogen from onshore wind, offshore wind, biomass resources, existing hydropower, concentrated solar power, and utility-scale photovoltaic solar power[41]

[40] Connelly et al. 2020. *Resource Assessment for Hydrogen Production*; M. Chung, E. Frank, A. Elgowainy, and K. Reddi. 2022. "Analysis of Hydrogen Export Potential." Presented at the DOE Hydrogen Program 2022 Annual Merit Review and Peer Evaluation Meeting, 8 June 2022. www.nrel.gov/docs/fy23osti/82700.pdf.

[41] Connelly et al. 2020. Resource Assessment for Hydrogen Production.

As shown in Figure 9, hydrogen production from wind power and solar photovoltaics offers a wide geographical range of options for both centralized and distributed production, with significant potential in almost every region of the country. And while most of the resource potential for concentrated solar power is in the southwestern region of the country, the resource potential for solid biomass is predominantly in the central and eastern regions.

In addition to hydrogen production resources, hydrogen infrastructure is expanding across the United States. This includes more than 1,600 miles of hydrogen pipelines (included in Figure 5), as well as existing and planned facilities for hydrogen liquefaction and large-scale salt cavern storage of gaseous hydrogen. There are currently 14 hydrogen liquefaction facilities operating today for a total capacity of more than 300 metric tons per day, with additional plants under construction or planned that will provide additional capacity up to 500 metric tons per day. There are three operating salt cavern facilities, with one additional planned, providing more than 330 GWh of hydrogen storage. Physical locations of the current and planned liquefaction plants and salt cavern storage facilities are shown in Figure 10. Figure 11 illustrates further opportunities for large-scale U.S. geologic storage beyond the facilities from Figure 10, including options that could leverage existing natural gas infrastructure, particularly in vicinities of the Regional Clean Hydrogen Hubs.

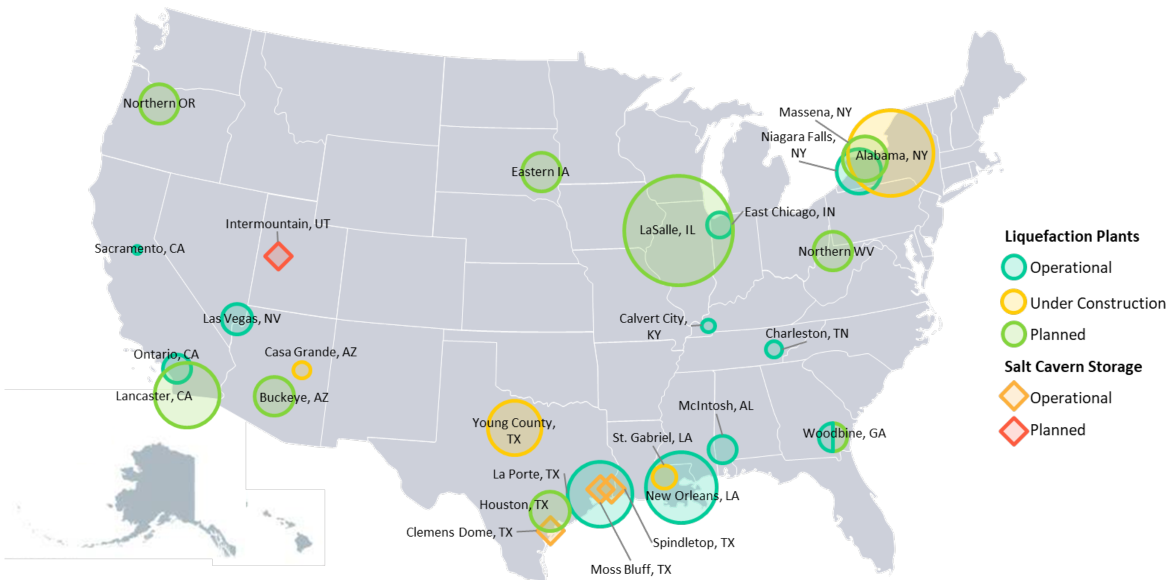


Figure 10. Existing and planned hydrogen liquefaction and salt cavern storage facilities in the United States[42]

[42] M. Wieliczko. 2024. "Hydrogen Liquefaction Capacity in the United States." DOE Hydrogen Program Record 24003. www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24003-hydrogen-liquefaction-capacity-united-states.pdf?sfvrsn=b894666d_1.

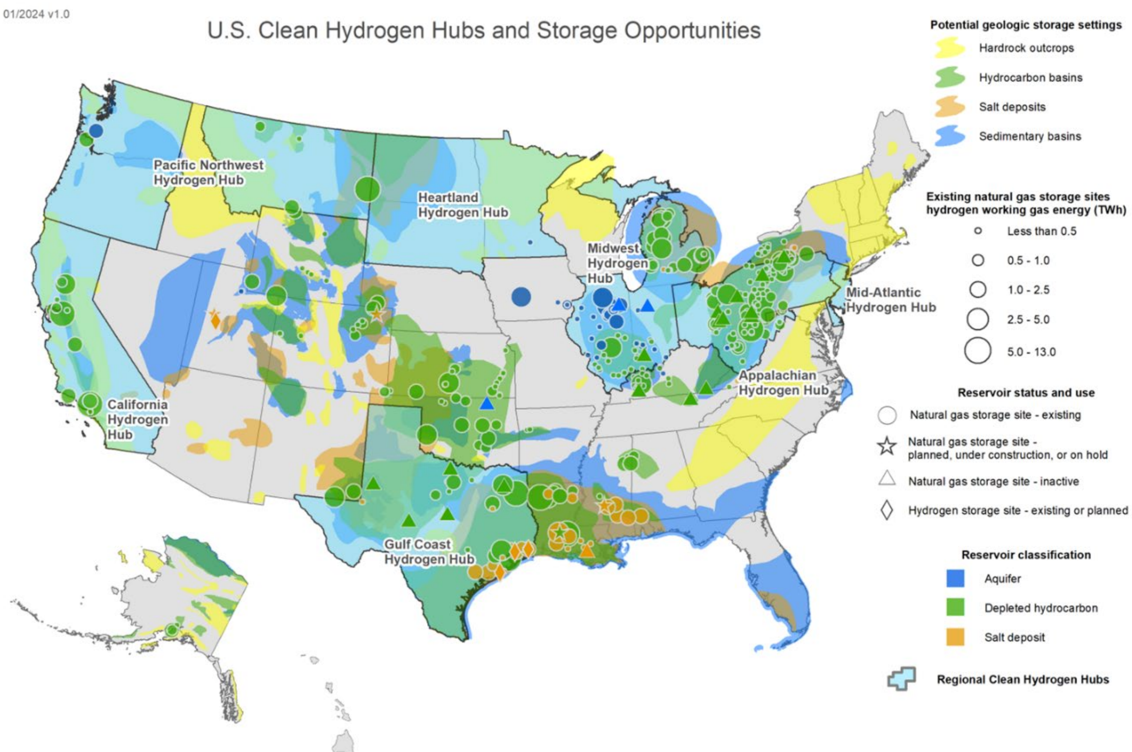


Figure 11. Subsurface hydrogen storage opportunities across the United States shown in relation to the Regional Clean Hydrogen Hubs, including options that could leverage current natural gas infrastructure[43]

In summary, as shown through the maps in this section, there are extensive opportunities to produce hydrogen from diverse domestic resources, and the Hydrogen Program has identified opportunities for using that hydrogen across multiple applications and sectors. Potential consumption by location is shown in Figure 12, as analyzed with input from industry stakeholders. Subsequent sections of this document outline the Hydrogen Program's strategy and R&D thrusts for each key focus area.

[43] National Energy Technology Laboratory. 2024. "SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration." Accessed Oct. 2, 2024. edx.netl.doe.gov/sites/shasta/.

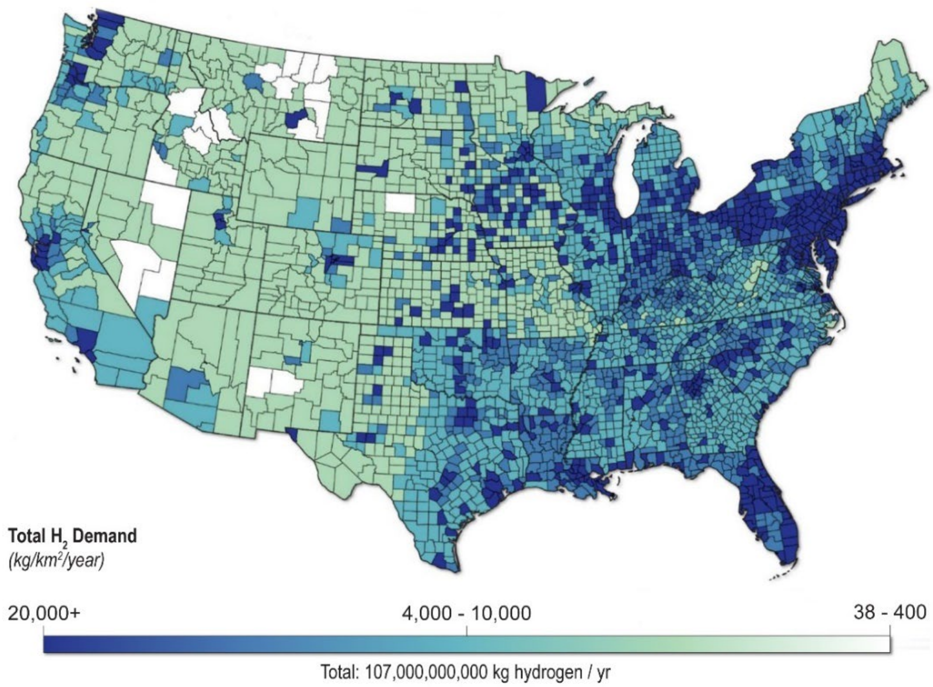


Figure 12. Serviceable consumption potential for hydrogen in the industrial and transportation sectors, natural gas, and storage[44]

Program Strategy

DOE funds RDD&D efforts that will provide the basis for the near-, mid-, and long-term production, delivery, storage, and use of hydrogen derived from diverse domestic energy sources. In order to capture the full range of benefits that hydrogen offers, the Hydrogen Program aims to advance hydrogen and related technologies for a wide variety of applications, with varying time frames for commercial adoption.

The Program has defined targets for hydrogen and related technologies based on the technical advances that are needed to be competitive in the marketplace with incumbent and other emerging technologies. Examples of the Program's overarching technical targets are listed to the right. More detailed technology- and application-specific targets and milestones are included in each office's multiyear planning documents. These targets have been identified through discussions with technology developers, the research community, and other relevant stakeholders.

Examples of Key DOE Hydrogen Program Targets

DOE targets are application-specific and developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the R&D community and inform the program's portfolio of activities. Please refer to the *U.S. National Clean Hydrogen Strategy and Roadmap* for specific milestones and dates.

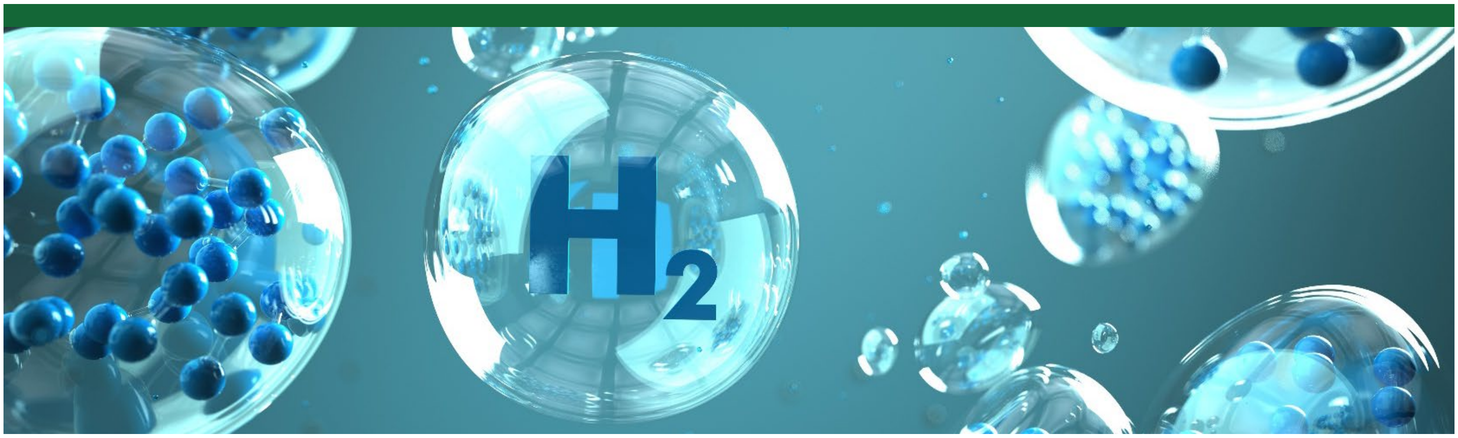
- $1/kg for clean hydrogen production.
- <$7/kg H_2 dispensed for heavy-duty transportation.
- Fuel cell system cost of $80/kW, 25,000-hour durability for long-haul heavy-duty trucks.
- Electrolyzer capital cost of $250/kW, 80,000-hour durability, and 65% system efficiency.
- Fuel cell system cost of $1,000/kW and 80,000-hour durability for fuel-flexible stationary high-temperature fuel cells.
- 9-ppm emissions of nitrogen oxides (NO_x) for 100% H_2 turbines, 2 ppm with selective catalytic reduction.

[44] M. Ruth, P. Jadun, N. Gilroy, E. Connelly, R. Boardman, A.J. Simon, A. Elgowainy, and J. Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77610. www.nrel.gov/docs/fy21osti/77610.pdf. Based on analysis conducted by national labs with industry input over the last several years. Includes ammonia, metals, biofuels, natural gas, synthetic hydrocarbons, refineries, grid storage, and light-, medium-, and heavy-duty fuel cell electric vehicles.

The Hydrogen Program is addressing key challenges to achieving the H2@Scale vision by conducting activities to:

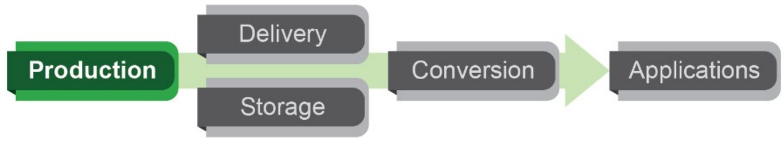
- Reduce costs and improve the performance and durability of hydrogen production, delivery, storage, and conversion systems.
- Address technological, regulatory, and market barriers that both limit the integration of hydrogen with conventional energy systems and reduce opportunities for exporting hydrogen.
- Assess and address environmental justice concerns to increase public benefit and support for hydrogen technologies.
- Explore opportunities for achieving large-scale adoption and use by aggregating disparate sources of hydrogen supply and demand.
- Develop and validate integrated energy systems utilizing hydrogen.
- Demonstrate the value proposition for new and innovative uses of hydrogen.

The following section provides additional details on the current status and needs in the key areas of RDD&D that the Hydrogen Program is pursuing, namely hydrogen production, delivery, storage, conversion, and applications.



3 Technology Focus Areas and RDD&D Thrusts

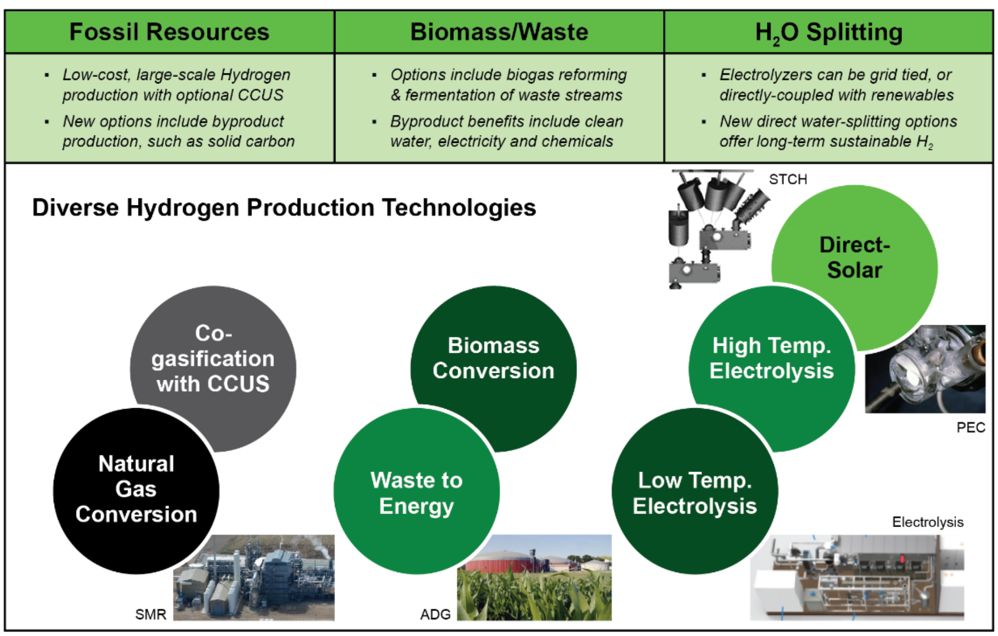
Hydrogen Production



Hydrogen can be produced from diverse domestic resources—renewable, nuclear, and fossil—in large, centralized plants or smaller facilities close to the point of use.

The United States has diverse and abundant natural resources to enable secure, clean, sustainable, large-scale, and affordable clean hydrogen production. Global demand for hydrogen across sectors is increasing, with a current worldwide consumption at approximately 97 MMT per year.[45] Of this, the United States currently produces and consumes almost 10 MMT annually, equivalent to just over 1 quadrillion Btu per year (1% of U.S. energy consumption).[46]

To meet this growing demand, a broad portfolio of hydrogen production pathway technologies is being explored and developed. As shown in Figure 13, these include technologies for tapping into fossil resources with CCUS, extracting hydrogen from biomass and waste stream resources, and splitting water.[47] This wide range of options opens regional opportunities to expand the hydrogen supply base across the country, offering clean hydrogen production capacities from a few hundred to hundreds of thousands of kilograms per day.



Novel and Hybrid Approaches including Geologic Hydrogen, Polygeneration, and Advanced Microbial Conversion

Figure 13. Diverse hydrogen production technologies.[48]

ADG = anaerobic digester gas; PEC = photoelectrochemical water splitting; STCH = solar thermochemical hydrogen

[45] International Energy Agency. 2024. *Global Hydrogen Review 2024*. iea.blob.core.windows.net/assets/3ece5ee4-7537-4992-8ba6-b83c994c3fd4/GlobalHydrogenReview2024.pdf.
[46] E. Connelly, A. Elgowainy, and M. Ruth. 2019. "Current Hydrogen Market Size: Domestic and Global." DOE Hydrogen and Fuel Cells Program Record 19002. www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19002-hydrogen-market-domestic-global.pdf?Status=Master.
[47] U.S. Department of Energy. 2015. "Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels, Technology Assessments, Hydrogen Production and Delivery." In *Quadrennial Technology Review 2015*. energy.gov/sites/prod/files/2015/11/f27/QTR2015-7D-Hydrogen-Production-and-Delivery.pdf.
[48] Katie Randolph. 2017. "HydroGEN: Accelerating Advanced Water Splitting Materials Discovery & Development." Presented at the 231st Electrochemical Society Meeting, 28 May–1 June 2017, New Orleans, LA.

Fossil Resources

Fossil fuels such as natural gas are the source of most of the hydrogen currently produced in the world. Today, approximately 95% of the hydrogen in the United States is produced by catalytic SMR in large central plants fed by the existing natural gas infrastructure.[49] Partial oxidation of natural gas (or other hydrocarbons), autothermal reforming (converting natural gas, steam, and oxygen to syngas), and co-gasification of fossil resources (e.g., with biomass or waste plastics)—all with CCUS—are other options leveraging domestic resources. Combining fossil-based processes with CCUS offers a promising near-term option for clean hydrogen production, and using CCUS when co-firing fossil-based feedstocks with biomass offers the potential for carbon-negative hydrogen as an additional environmental benefit. To date, advanced production systems based on reforming of natural gas have been demonstrated that are capable of producing low-carbon hydrogen for less than $2/kg with CCUS. For example, industry has demonstrated a fully integrated hydrogen production facility at the Port Arthur CCUS project at the Valero Refinery.[50] While SMR and gasification with CCUS are mature industrial technologies that can produce low-carbon hydrogen for a cost of less than $2/kg today,[51] ongoing RDD&D in the areas of catalysis, separations, controls, polygeneration, capital cost reductions, process intensification, and modularization with advanced design methods (e.g., parametric design), including through the use of artificial intelligence, can further reduce the cost of fossil-based hydrogen production while further reducing CO_2 emissions. Other emerging approaches for clean hydrogen production related to fossil resources include the direct pyrolysis of methane into hydrogen and solid carbon coproducts and geologic production through subsurface thermocatalytic processes. Research advances in diverse approaches, including geologic extraction, as well as reforming and gasification technologies with CCUS, target improved performance with reductions in capital and operating costs to achieve hydrogen production at less than $1/kg.

Biomass and Waste Stream Resources

Domestic biomass and waste stream resources, with the potential for more than a billion dry tons of feedstock annually,[52] can be leveraged for sustainable hydrogen production. Applicable categories of feedstocks include primary biomass energy sources such as poplar, willow, and switchgrass, as well as biogas produced from anaerobic digestion of organic residues from sources such as landfill, agricultural waste, and municipal solid waste.[53] Primary biomass can be gasified using well-established technologies, or even co-fed with coal or waste plastics in the gasification process. It can also be processed into bio-derived liquids for subsequent reforming into hydrogen and, when coupled with CCUS, could potentially produce carbon-negative hydrogen. Biogas, with additional cleanup requirements, can be reformed to produce hydrogen using a process similar to SMR. Certain waste stream feedstocks can be used to produce hydrogen through biological-based processes such as fermentation and microbial-assisted electrolysis, or through novel thermal and nonthermal plasma-based processes. The cleaning up of waste streams that occurs in these processes is an additional benefit. Depending on feedstock availability and cost, some approaches—including gasification and steam reforming of biomass and waste streams—may be economically competitive in the near term. To enable broader adoption, RDD&D is needed to address challenges for both near- and longer-term technologies, including improvements in conversion efficiency (e.g., through advanced catalysis and separations, as well as process intensification) and reductions in the costs of pretreating and transporting feedstocks.

[49] U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Clean Hydrogen. An update to this report is forthcoming.
[50] McNaul et al. 2023. Hydrogen Shot Technology Assessment.
[51] McNaul et al. 2023. Hydrogen Shot Technology Assessment.
[52] U.S. Department of Energy. 2024. *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*. M.H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/SPR-2024/3103. www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf.
[53] National Research Council and National Academy of Engineering. 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C.: National Academies Press. nap.nationalacademies.org/catalog/10922/the-hydrogen-economy-opportunities-costs-barriers-and-rd-needs.

Water-Splitting Technologies

There are a number of processes that split water into hydrogen and oxygen using electric, thermal, or photonic (light) energy from diverse, sustainable domestic sources (e.g., solar, wind, nuclear). Low-temperature electrolyzers (including liquid alkaline and membrane-based electrolyzers) that use electricity to split water offer near-term commercial viability, with units available today at the multimegawatt scale.

> **Hydrogen Production Target**
>
> **Affordable clean hydrogen from diverse domestic resources:**
>
> - <$2/kg by 2026 for electrolysis as referenced in the Bipartisan Infrastructure Law.
> - $1/kg by 2031 as referenced in the Hydrogen Shot.

These electrolyzers can be coupled to the electric grid or integrated directly with distributed generation assets to produce hydrogen for various end uses. The cost of clean hydrogen produced from low-temperature electrolysis depends strongly on the electricity cost, currently ranging from $5 to $7/kg H_2 for various clean electricity pricing scenarios.[54] One pathway to achieving cost-competitive hydrogen at less than $2/kg will require pairing low-cost, high-capacity-factor renewable electricity—for example, from identifying unique locations to optimally site hybrid energy systems leveraging wind and solar resources—with ongoing advancements in electrolyzer technologies. However, more work is needed to reduce the cost of energy storage, which could help with the integration of intermittent renewables, to achieve consistent, widely available, low-cost and low-carbon electricity. Another pathway to achieving this cost target is through integration of electrolyzers with nuclear power generation. The capacity factor of most nuclear power plants approach 95%, providing full power 24/7. Thus, the existing fleet of nuclear plants offers a promising pathway for achieving a clean, reliable, low-cost source of energy for hydrogen when hydrogen is produced "behind the meter" or without using the transmission and distribution system. There may be challenges for producing hydrogen with nuclear power, including existing obligations to produce power for the grid and the economic potential for hydrogen-based revenue compared to the electricity market. In the future, advanced reactors would also have the advantage of a high-capacity factor. However, the cost of electricity from new nuclear plants is expected to be higher than the existing fleet, and more work is needed to develop and reduce the cost to deploy advanced nuclear power plants. High temperature electrolyzers can leverage both electricity and heat from generation sources such as nuclear, geothermal, concentrated solar power plants, or fossil with CCUS to improve conversion efficiencies, further reducing cost. With wind and photovoltaic solar power, high temperature electrolyzers have high efficiency even when they use electrical heating. Reversible fuel cells, currently under development, combine the functionality of electrolyzers and fuel cells, either using electricity to split water into hydrogen and oxygen, or using hydrogen and oxygen to produce electricity and water. Longer-term pathways for direct water splitting, without the need for electricity, include thermally driven chemical looping processes such as solar thermochemical systems, as well as light-driven photoelectrochemical processes. Ongoing RDD&D—at the materials, component, and system levels—will be needed to address efficiency, durability, and cost challenges in all water-splitting processes.

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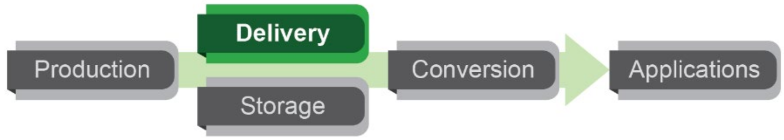
[54] McKenzie Hubert, David Peterson, Eric Miller, James Vickers, Rachel Mow, and Campbell Howe. 2024. "Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology." DOE Hydrogen Program Record 24005. www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf?sfvrsn=8cb10889_1.

Common RDD&D Thrusts for Hydrogen Production

- New catalysts and electrocatalysts with reduced platinum group metals.
- Modular gasification and electrolysis systems for distributed and bulk power systems.
- Low-cost and durable membranes and separations materials.
- Novel, durable, and low-cost thermochemical and photoelectrochemical materials.
- Accelerated stress tests and understanding of degradation mechanisms to improve durability.
- Reduced capital costs for reforming technologies, including autothermal reforming.
- Improved balance-of-plant components and subsystems, such as power electronics, purification, and warm gas cleanup.
- Component design and materials integration for scale-up and manufacturability at high volumes.
- Reversible fuel cell systems including for polygeneration of electricity and hydrogen.
- System design, hybridization, and optimization, including process intensification.

Hydrogen Delivery



Hydrogen can be transported in gaseous form, in liquid form, or in chemical carriers. Various technology options are needed for distributing and dispensing hydrogen for different end uses.

To support a wide range of applications, delivery infrastructure for hydrogen may incorporate multiple technology pathways capable of transporting hydrogen in various forms, including as a gas in pipelines and high-pressure tube trailers, as a liquid via tanker trucks, and using chemical hydrogen carriers. Different technologies for dispensing hydrogen may also be needed depending on how the hydrogen is transported, stored, and utilized. The technologies required to support these delivery pathways are at various stages of development, but they must ultimately be both affordable and meet or exceed the level of safety, convenience, reliability, and energy efficiency expected from existing infrastructure for other fuels, as well as support addressing environmental injustices for overburdened communities.

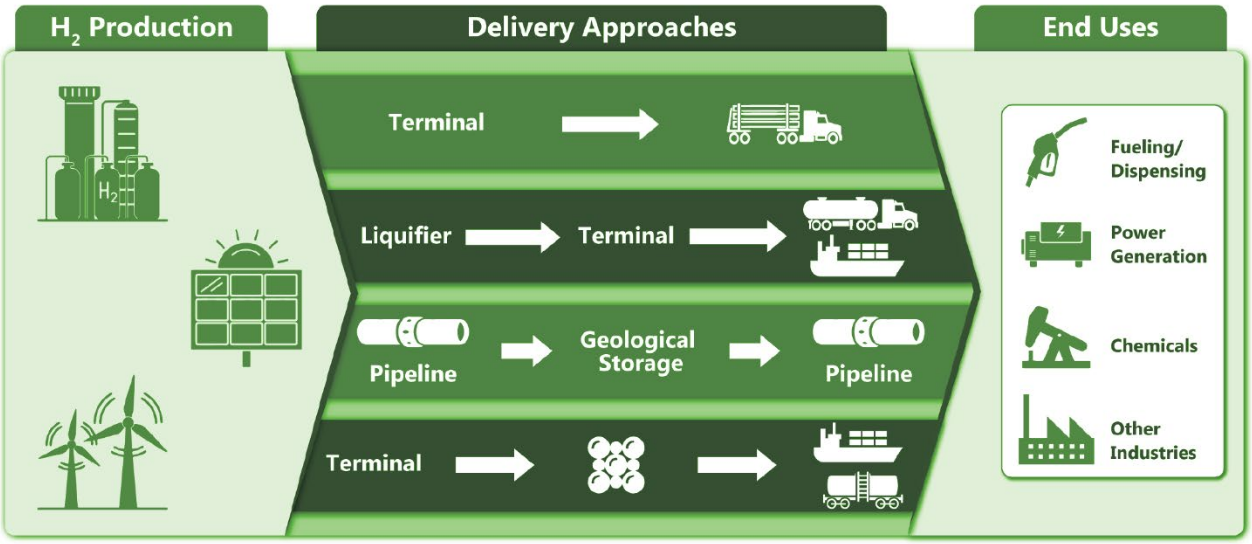


Figure 14. The four main methods of hydrogen delivery: gaseous tube trailers, liquid tankers, pipelines, and chemical hydrogen carriers

As shown in Figure 14, there are four main hydrogen methods of hydrogen delivery at scale: gaseous tube trailers, liquid tankers, pipelines (for gaseous hydrogen), and chemical hydrogen carriers. Each of these pathways is described below.

Tube Trailers

Hydrogen is typically transported under high pressure in tube trailers when the quantity of hydrogen delivery is small (≤1 tonne/day). Tube trailers are likely to remain an essential technology to supply growing markets that use relatively small amounts of hydrogen or do not yet have predictable demand. Today, tube trailers are usually filled using liquid hydrogen—the liquid hydrogen is pressurized and then vaporized into gaseous form. As markets of small-scale hydrogen consumers expand, this approach will be less efficient than filling tube trailers directly at a gaseous hydrogen production facility. Such co-located gaseous tube trailer terminals are now under development. RDD&D efforts will be needed to enhance the lifetime of pressure vessels on board tube trailers, reduce the cost of high-pressure composite tube trailers, and increase the capacity of compressors used at tube trailer terminals.

Liquid Hydrogen

Liquid tankers are used to transport hydrogen for applications where there is significant and stable hydrogen demand, but in areas where overall regional hydrogen demand is not large enough to warrant pipelines. Liquid tanks on board marine vessels are also being explored for international shipping of low-carbon hydrogen for export markets. Liquid tankers commonly store more than 5 times as much hydrogen per load than gaseous tube trailers. In some cases, liquid hydrogen is also used because it is extremely pure and offers lower risk of contamination when compared with hydrogen supplied by gaseous pathways. Existing liquefaction plants in North America vary in production size from 6 to 30 tonnes/day.[55] The current process and technologies for hydrogen liquefaction are relatively mature. The process involves cooling gaseous hydrogen using liquid nitrogen and then compressing and expanding the precooled gas until it condenses into a liquid at −253°C (−425°F). This process is both capital- and energy-intensive. The energy consumed in conventional liquefaction is equal to about 35% of the energy content of the liquefied hydrogen. To address this challenge, RDD&D is needed to enable novel nonmechanical approaches to liquefaction, such as the use of magnetocaloric materials and processes that have potential to enable hydrogen liquefaction at twice the efficiency of conventional approaches.

Pipelines

Hydrogen pipelines are often used in regions where there is significant demand (thousands of tonnes per day) and that demand is expected to remain stable for a long duration (15–30 years). Hydrogen pipelines are capital-intensive, but when the quantity of hydrogen demand is high, they have a lower levelized cost over time. Today, more than 2,575 kilometers (1,600 miles) of dedicated hydrogen transmission pipelines serve the United States,[56] and these are mostly concentrated in the Gulf Coast due to the substantial hydrogen demand at petroleum refineries. While pipelines are the most energy-efficient approach to transporting hydrogen, their deployment is challenged by their high capital costs. RDD&D efforts needed to enable lower-cost pipelines include development of high-throughput compressors to enable use of larger pipelines; assessment of novel low-cost materials for use in pipelines (e.g., to assess compatibility of higher-strength steels with hydrogen); and first-of-a-kind demonstrations of novel pipeline technologies (e.g., fiber-reinforced polymer piping). Blending of hydrogen into existing pipelines commingled with natural gas, "city gas," or other products is also possible as the economy builds demand. Some applications can use blends of hydrogen, while others may require separation of hydrogen and natural gas at the end use, as described further in the Applications section.

Chemical Hydrogen Carriers

Another emerging method to transport large amounts of hydrogen is the use of chemical hydrogen carriers, which offer the potential to carry more hydrogen than tube trailers and at lower cost. Chemical hydrogen carriers are liquid- or solid-phase materials that can chemically bond with hydrogen to "carry" it at low pressure and near-ambient temperatures but can then release the hydrogen on demand. They may be ideally suited for applications where hydrogen demand is substantial, but not stable enough to warrant pipeline construction. They also offer the potential for significantly higher energy density compared with gaseous or even liquid hydrogen transport, thereby reducing hydrogen delivery cost. Chemical hydrogen carriers can be broadly classified as one-way or two-

[55] IHS Markit. 2018. Chemical Economics Handbook.
[56] U.S. Department of Energy. 2023. Pathways to Commercial Liftoff: Clean Hydrogen. An update to this report is forthcoming.

way carriers. One-way carriers are materials that deliver hydrogen to a given end use without the need to be reprocessed (i.e., rehydrogenated) for further use; an example is ammonia (NH_3) that can be delivered for use in a fertilizer production facility or "cracked" to separate the hydrogen from nitrogen for other end uses. Two-way carriers are those whose byproducts are typically returned for processing for reuse or disposal after the hydrogen is released. An example is methylcyclohexane, which produces toluene with the release of hydrogen, and the toluene can be reprocessed into methylcyclohexane through hydrogenation. The use of chemical hydrogen carriers is in the early stages of commercialization, and RDD&D efforts are needed to increase the hydrogen-carrying capacity of these materials and improve the charge and discharge rates, reversibility, and overall round-trip efficiency. Some carriers, like ammonia, can also be used for direct power generation without intermediate hydrogen release such as in turbines, internal combustion engines, and direct fuel cells, but more R&D is needed to achieve commercial viability.

Hydrogen Dispensing and Fueling

Once hydrogen is transported to the site of use, it may need to be conditioned by pressurizing, cooling, and/or purification, and it is commonly stored on-site in bulk. These processes can involve a number of different systems—for example, hydrogen fueling stations for vehicles (light, medium, and heavy duty) typically have high-pressure compressors, storage vessels, and dispensers. These systems are designed to enable hydrogen fueling per standard protocols. For light-duty refueling, these protocols are well established—for example, the fueling pressure is typically 700 bar (approximately 10,000 psi or 70 MPa)—and the technologies are commercially deployed in more than 50 retail hydrogen fueling stations for light-duty fuel cell electric vehicles in the United States. For medium- and heavy-duty fuel cell electric vehicles, fueling standards are still under development, and those will inform the equipment requirements for future high-throughput stations.

Example: Hydrogen Delivery Targets

Large-scale hydrogen delivery, distribution, and dispensing at:

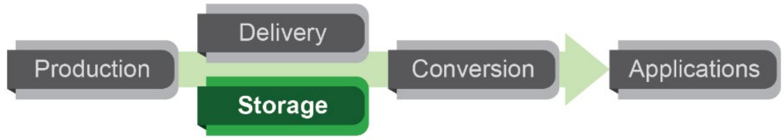
- <$7/kg for transportation end uses in early markets.
- <$4/kg for ultimate market expansion for high-value products.

RDD&D efforts are needed to reduce the cost, improve the reliability, and increase the throughput of hydrogen dispensing systems and other related systems at the fueling station or point of use. These activities aim to enhance the reliability of materials used in dispensing hoses and seals (e.g., in compressors); improve the life of dispensing hoses through novel designs; develop novel designs for compressors, cryogenic transfer pumps, and dispensers to ensure they have sufficient throughput for the medium- and heavy-duty market; and conduct materials research to increase the life and capacity of high-pressure storage vessels. Additional application-specific challenges are discussed in the Applications section.

Common RDD&D Thrusts for Hydrogen Delivery

- Materials compatibility with hydrogen at high pressures and/or low temperatures.
- Innovations in hydrogen liquefaction.
- Carrier materials and catalysts for hydrogen storage, transport, and release.
- Innovative components for low-cost distribution and dispensing (e.g., compressors, cryopumps, storage vessels, dispensers, nozzles).

Hydrogen Storage



Hydrogen may need to be stored in bulk prior to being delivered, during the delivery process, or at the point of use. A variety of technology solutions for hydrogen storage will be needed to meet different application-specific requirements.

Hydrogen has nearly 3 times the energy content of gasoline per unit of mass,[57] but the volumetric energy density of gaseous hydrogen is low, making it difficult to store in compact containers. To overcome this challenge, hydrogen is usually stored using *physical processes* as a gas or cryogenic liquid; it can also be stored using *material-based processes* that incorporate hydrogen in chemical compounds. The current portfolio of hydrogen storage options is shown in Figure 15.

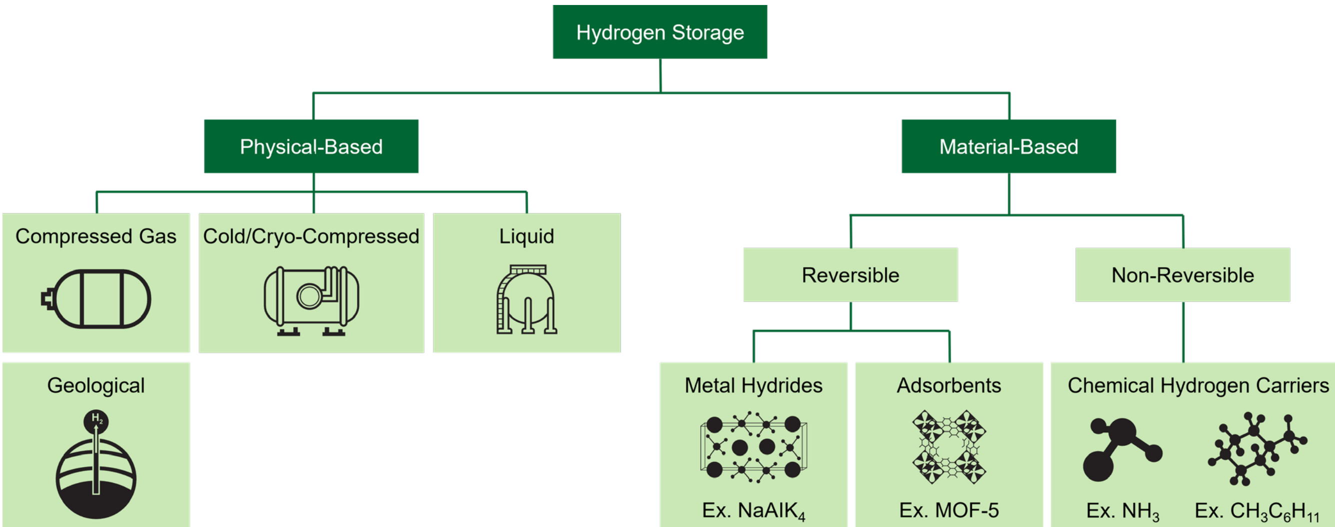


Figure 15. Current portfolio of hydrogen storage options.

Includes physical-based gaseous and liquid storage in tanks and reversible and nonreversible materials-based storage.[58] Approaches for very large-scale bulk storage (such as geological storage) are also under investigation.

Physical-Based Storage

For a range of transportation and other stationary and power generation applications, gaseous hydrogen is usually stored in pressurized tanks, which are typically constructed of all-metal or composite overwrapped pressure vessels. Examples include carbon fiber composite overwrapped tanks with metal or polymer liners for onboard storage of hydrogen at 350 bar (5,076 psi) and 700 bar (10,153 psi) in commercial material-handling equipment and fuel cell electric vehicles, respectively. Larger all-metal or composite overwrapped pressure tanks are used for bulk gaseous hydrogen storage at hydrogen refueling stations, and in various chemical and stationary power applications. Large-scale geologic storage within salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs offers opportunities for long-duration energy storage applications.

[57] The energy content of hydrogen is 33 kWh/kg, while gasoline's is 12 kWh/kg, based on lower heating value.

[58] Reversible materials are able to release or uptake hydrogen directly through changes in temperature or pressure, whereas nonreversible materials require additional chemical or physical processing to effect reuptake of hydrogen (also referred to as "regenerable" materials).

One example is the world's largest hydrogen storage salt cavern located in Beaumont, Texas, which currently serves as a buffer in the Gulf Coast hydrogen pipeline system, storing more than 7,000 tonnes of hydrogen underground.

Additional RDD&D efforts are needed to reduce the cost and ensure the safety of gaseous hydrogen storage. For example, efforts are currently underway to develop low-cost carbon fiber and thereby address the major cost contributor in high-pressure composite overwrapped tanks. For larger tanks for bulk storage of hundreds of tons of hydrogen, novel designs, materials, and controls to accommodate fuel supply requirements are being investigated. Broader safety-related research efforts are also addressing materials compatibility issues and fatigue, as well as mitigation of safety issues related to setback distances and underground storage.

While compressed hydrogen is typically stored at ambient temperatures, reducing the temperature to cold or cryogenic temperatures can significantly increase hydrogen's density. For instance, at 15°C and 700 bar, hydrogen has a density of 40 g/L; at −150°C and 700 bar, its density is 67 g/L; and at −253°C and 1 bar (at which point it is a liquid right at boiling point), it has a density of 71 g/L.[59] In liquid form, hydrogen is stored at extremely low cryogenic temperature in highly insulated double-walled tanks—these tanks are commercially available and used today for industrial-scale storage and transport.[60] The energy densities in both liquid and cryo-compressed hydrogen storage systems offer important advantages for a number of applications that require extended operating ranges and high-throughput fueling, including medium- and heavy-duty vehicles, marine applications, and trains. However, the need for insulation, as well as the boil-off and venting that occur from extended dormancy, present added cost and challenges to system performance. Material-, component-, and system-level RDD&D is needed to address these challenges.

Material-Based Storage

As an alternative to gaseous or liquid storage, hydrogen can also be densely stored at low pressures in certain material compounds. Different categories of material-based storage include metal hydrides, adsorbents, and chemical hydrogen storage. Metal hydrides store hydrogen atoms by chemically bonding them to atoms in the compound structure. Examples include complex hydrides such as magnesium borohydride. Adsorbents, such as microporous super activated carbons or metal-organic frameworks, utilize weak bonding between molecular hydrogen and adsorbent surfaces and typically require lower storage temperatures. Hydrogen storage via metal hydrides and adsorbents is considered reversible, since hydrogen uptake and release can be controlled by changing the temperature and/or pressure. Many chemical hydrogen carriers, including materials such as methylcyclohexane, have the potential to store large quantities of hydrogen by mass and volume. With these materials, however, thermal or catalytic chemical reactions are needed both to bind and release the hydrogen, and these processes can result in significant round-trip energy losses. Liquid chemical hydrogen carriers compatible with large-scale storage and transport include common compounds such as ammonia and methanol. Currently no material-based storage approaches are commercially mature, and foundational material- and system-level RDD&D

Example: Hydrogen Storage Targets

- Onboard hydrogen storage systems for transportation: $8/kWh stored at 2.2 kWh/kg and 1.7 kWh/L.
- High-volume cost of high-strength carbon fiber for tanks: $14/kg.[61]

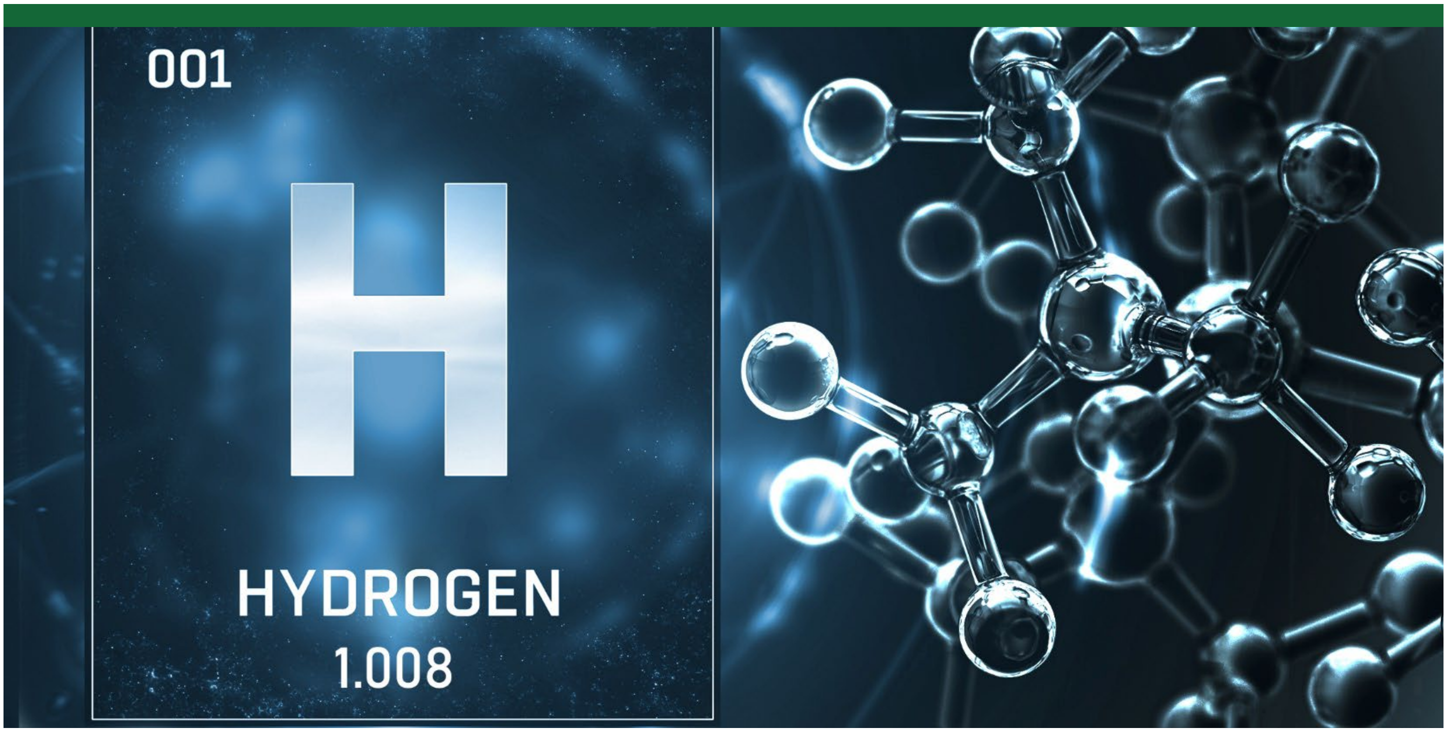
[59] For reference, the energy density of liquid hydrogen (71 g/L) is equivalent to 2.4 kWh/L.
[60] The scale of liquid hydrogen storage vessels for different industrial end uses ranges from hundreds of gallons up to more than a million gallons.
[61] Target based on small-scale onboard storage tanks (5.6 kg H_2); the cost of carbon fiber becomes less crucial for larger systems, as they require less carbon fiber per kilogram of H_2.

is needed for the discovery and optimization of viable hydrogen storage materials capable of achieving the cost, energy density, and hydrogen uptake and release required for commercialization.

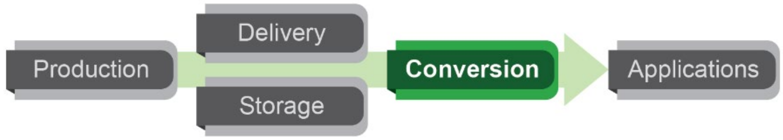
The most suitable type of storage depends on a number of factors such as the end-use application, the amount of hydrogen needed, geographical and geological constraints, and the required flow rates. For instance, a 500-MW turbine operating on hydrogen will require approximately 500–600 tons of hydrogen per day, more than 1,000 tons for two days of storage, or an equivalent amount of energy stored as a chemical. A 30-MW data center would require about 45 tons per day (or about 90 tons on-site for two days of backup power). Today's long-haul fuel cell truck manufacturers are targeting stations with a few tons per day of hydrogen. Onboard storage can range from a few grams for small-scale drones, 100 kilograms for fuel cell trucks, and more than a ton for certain marine and rail applications. Examples of key targets and RDD&D thrusts to address key hydrogen storage challenges are shown here.

Common RDD&D Thrusts for Hydrogen Storage

- Reduced costs at the material-based, component, and system levels.
- Low-cost, high-strength carbon fiber for high-pressure tanks.
- Materials compatible with hydrogen for durability and safety.
- Cryogenic RDD&D for liquid hydrogen and cold/cryo-compressed storage.
- Discovery and optimization of hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements.
- Optimization for round-trip efficiency using chemical hydrogen carriers.
- Storage of hydrogen in the form of a chemical energy carrier that can be used in hydrogen turbines.
- Identification, assessment, and demonstration of geologic storage of hydrogen.
- Systems analysis for the export of hydrogen and hydrogen carriers.
- Analysis to refine targets for a broad range of storage options and end uses.
- Sensors and other technologies needed to ensure storage of hydrogen is safe, efficient, and secure.



Conversion



After hydrogen is produced, delivered, and stored, it is then converted into useful energy using combustion or fuel cells.

As discussed in previous sections, hydrogen is an *energy carrier* that is produced using energy and feedstocks such as water, biomass, natural gas, coal, oil, and wastes such as wastewater and plastics. To be useful, the energy carried by hydrogen must be converted into a different form, such as electricity and/or heat. This conversion can be accomplished through combustion using turbines or reciprocating engines, or through an electrochemical process using a fuel cell. There are a number of opportunities to design hybrid energy systems—for example, using high- or low-temperature stationary fuel cells integrated with gas turbines in large-scale combined-cycle hybrid systems, which use both conventional and fuel cell energy conversion technologies. Other hybrid systems are also being considered, as discussed in the Applications section.

Fuel Cells

A fuel cell uses the chemical energy of fuels such as natural or synthetic gas and hydrogen to produce electricity and thermal energy. If fuel cells use hydrogen fuel directly, water is the only byproduct emitted—there is no carbon dioxide and no pollutants such as NO_x. Fuel cells can be more efficient than internal combustion engines because the electrochemical reactions in a fuel cell generate electricity directly—while combustion has to convert the energy in the fuel first into mechanical energy and then into electrical energy. Fuel cell efficiencies of more than 60% have been demonstrated,[62] and more than 80% efficiency is possible when fuel cells are used in combined heat and power applications.[63]

Example: Polymer Electrolyte Membrane Fuel Cell (PEMFC) Target for Long-Haul Trucks

- $80/kW fuel fell system cost.
- 25,000-hour durability.

Fuel cells are similar to batteries in that they are composed of positive and negative electrodes separated by an electrolyte or membrane, and both are highly efficient. Fuel cells, however, do not need to be recharged the way batteries do, so they can run for extended periods as long as fuel and air are provided. In fuel cells, power and energy are decoupled and can be tuned independently—i.e., for a fixed fuel cell stack, more hydrogen allows higher energy capacity without changing the fuel cell size or power. Like batteries, fuel cells have advantages over combustion engines: they have no moving parts, are quiet, and require no oil changes and minimal maintenance. Fuel cells are also easily scalable, as individual cells can be stacked together to provide a wide range of power. They can range in size from less than a watt for portable power to hundreds of kilowatts for heavy-duty applications and many megawatts for large-scale stationary power.

[62] H. Lohse-Busch, M. Duoba, K. Stutenberg, S. Iliev, M. Kern, B. Richards, M. Christenson and A. Loiselle-Lapointe. 2018. *Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai*. Lemont, IL: Argonne National Laboratory. ANL/ESD-18/12. publications.anl.gov/anlpubs/2018/06/144774.pdf.
[63] J. Spendelow, T. Nguyen, C. Houchins, K. Epping Martin, and D. Papageorgopoulos. 2011. "Medium-scale CHP Fuel Cell System Targets." DOE Hydrogen and Fuel Cells Program Record 11014. www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf.

Common R&D Thrusts for PEMFCs

- Improved catalyst activity and durability with reduced platinum group metal catalyst loading.
- High-temperature-tolerant, low-cost, and durable membranes and ionomers.
- Improved component design and materials integration to optimize manufacturable and scalable electrode structures for membrane electrode assemblies.
- Advanced bipolar plates, coatings, and gas diffusion layers.
- Accelerated stress tests, improved understanding of degradation mechanisms, and mitigation approaches.
- Improved balance-of-plant components, including compressors and power electronics.
- Standardized, modular stacks and systems for multiple heavy-duty applications.
- Improved hybridization and optimized system design.

There are a number of types of fuel cells, all of which have particular advantages that make them well suited for various applications. The key features that distinguish the different types of fuel cells include type of electrolyte, operating temperature, and the level of hydrogen purity required.

Polymer electrolyte membrane fuel cells typically operate at about 80°C and can respond quickly to changing loads, making them suitable for transportation applications as well as stationary, backup, or portable power applications that require fast startup times or must react to variable loads. *Solid oxide fuel cells* (SOFCs) operate at much higher temperatures (typically 800°C to 1,000°C) and are more suitable for use in modular and utility-scale stationary power systems, since the high temperatures make rapid startup challenging. There are also intermediate-temperature fuel cells such as *molten carbonate* (600°C–700°C) and *phosphoric acid fuel cells* including polymer-phosphoric-acid-based systems (150°C–200°C), as well as other low-temperature fuel cells like *alkaline fuel cells* and emerging *alkaline exchange membrane fuel cells* (≤80°C). Application-specific targets are developed by each DOE office to guide activities and ensure that PEMFC and SOFC technologies are on the pathway to competitiveness in terms of cost, performance, durability, and reliability. Two examples of application-specific targets and common RDD&D thrusts for DOE's efforts in PEMFCs and SOFCs are provided in this section; additional targets for various fuel cell applications can be found in the RDD&D plans of the individual program offices.

Example: SOFC Target for Stationary Power Generation

- $1000/kW fuel cell system cost
- 80,000 hour durability

Common RDD&D Thrusts for SOFCs

- Materials R&D to reduce cost and address issues related to high-temperature operation.
- Management of heat and gas flow across the stack.
- Addressing stack and balance-of-plant systems integration, controls, and optimization for load-following and modular applications.
- Internal reforming of carbon-neutral fuels for directly fed fuel cells.
- Improved balance-of-plant components, including compressors and power electronics.
- Standardized, modular stacks.
- Improved understanding of impacts of impurities on materials and performance.
- System design, hybridization, and optimization, including for reversible fuel cells.

As illustrated in Figure 16, fuel cells can use a wide range of fuels and feedstocks and can provide power for several applications across multiple sectors. In addition to these applications, DOE is exploring the use of fuel cells for trigeneration, which can use fuels such as coal syngas, biogas, or natural gas to coproduce power, heat, and hydrogen. Efforts are also focused on low- and high-temperature reversible fuel cells that can operate in two modes, to produce either hydrogen or electricity. (As noted in the Hydrogen Production section, in *electrolysis mode*, a reversible fuel cell uses electricity and water to produce hydrogen, and in *fuel cell mode*, it uses hydrogen to produce electricity and water.) Reversible fuel cell systems would offer the ability to provide easily dispatchable power in a single unit, using only water as a feedstock. For example, a coal gasification facility can generate hydrogen for use in an SOFC to produce electricity, while during periods of low electricity demand the SOFC can operate reversibly to produce hydrogen for storage and/or chemical production. Alternatively, reversible fuel cells can be integrated with intermittent renewables to generate hydrogen from electricity that would otherwise be curtailed during periods of low demand. That hydrogen can subsequently be utilized to generate electricity during times of high-power demand when the renewable energy source (e.g., wind, solar) is not available.

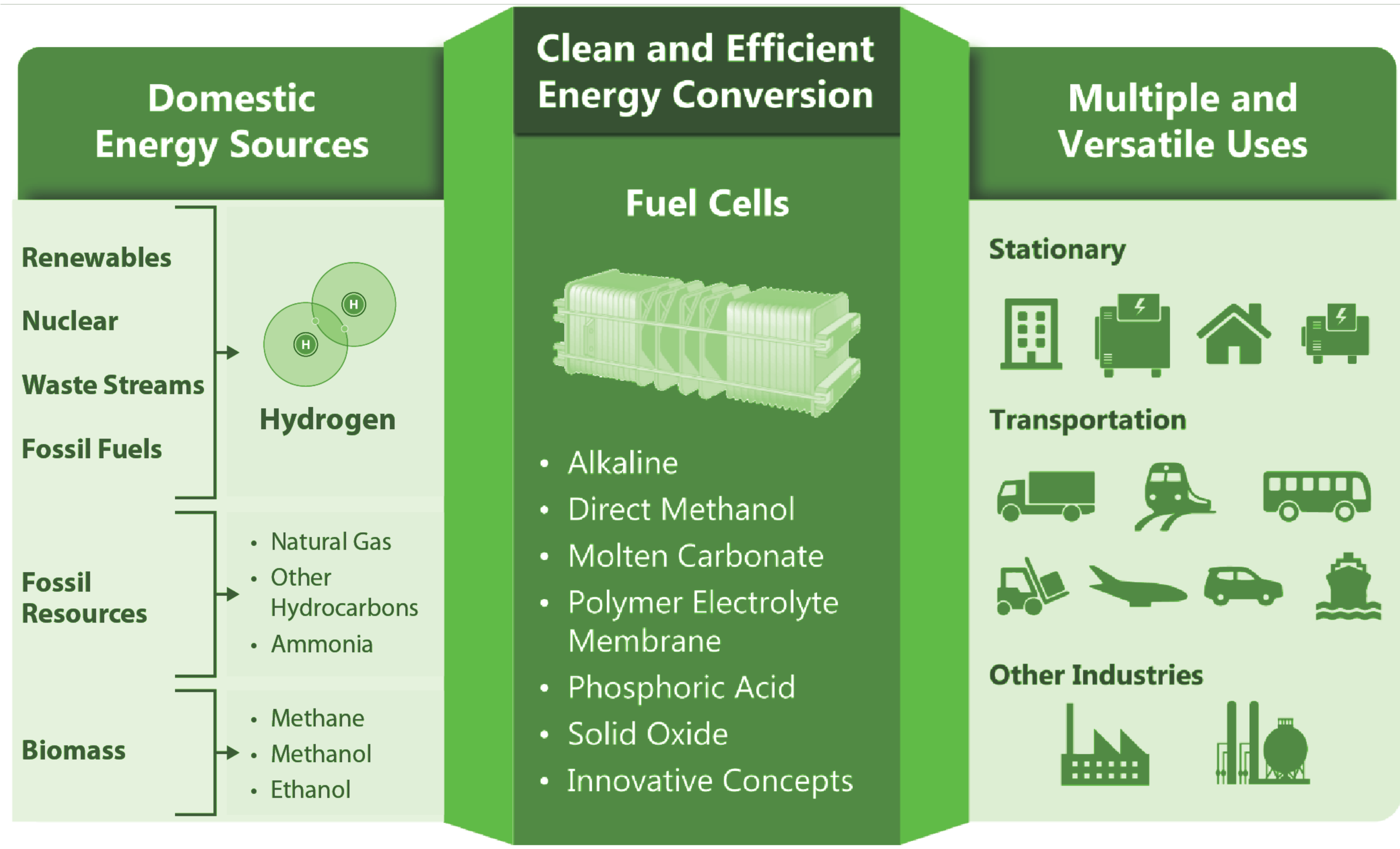


Figure 16. Versatility of fuel cells

For all these applications, there is a common need to reduce cost and improve durability, as well as maximize community benefit and minimize negative impact while maintaining efficiency. Depending on the type of fuel cell, a key contributor to cost is the catalyst, typically based on platinum group metals, which rely on foreign imports. Other key components needing RDD&D improvements to meet cost and durability targets are membranes or electrolytes; bipolar plates, which serve multiple functions including water removal and the collection of the electric current produced; and other components such as gas diffusion layers. The environmental sustainability of polymer membrane materials, such as perfluorosulfonic acid, is a potential concern. Reliable and low-cost balance-of-plant components such as compressors, blowers, and power electronics are also required.

Combustion

Hydrogen can be combusted in the same manner as natural gas, synthetic gas, diesel, gasoline, and other common fuels. The benefit of using hydrogen is that no carbon dioxide is produced, and water is the only major byproduct. The use of hydrogen in engines was successfully demonstrated decades ago by both NASA, which has used hydrogen in the main engines of space shuttles, and by the Department of Defense, which has used hydrogen in unmanned rocket engines.

The advantages of power generation using hydrogen combustion include fuel flexibility through the ability to burn hydrogen and blends of fossil fuels; fuel security through integration with hydrogen storage; the ability to meet large demands for electricity; and the flexibility to follow loads from variable generation.

Recently, major players in the worldwide power generation industry have been focusing more attention on hydrogen turbines, particularly for large-scale generation. Industry has developed materials and systems to increase the concentration of hydrogen that can be combusted, and these advances have allowed hydrogen to be fired at concentrations over 90% in simple-cycle turbines or aeroderivative machines, and at concentrations of up to 50% in large-frame combined-cycle turbines.[64] Large-frame turbines capable of firing hydrogen/natural gas blends of up to 30% hydrogen and aeroderivative turbines capable of firing over 90% hydrogen are commercially available today.

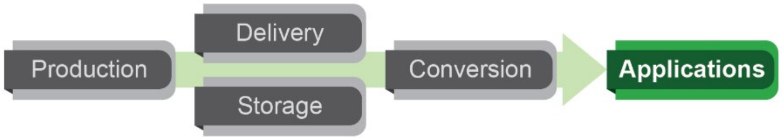
Common RDD&D Thrusts for Hydrogen Combustion

- Enable wider range of acceptable hydrogen concentrations (up to 100%) in simple and combined cycles.
- Improve understanding of combustion behavior and optimization of component designs for low-NO_x combustion.
- Apply and develop advanced computational fluid dynamics with reacting flows.
- Develop advanced manufacturing techniques for combustors.
- Develop new materials, coatings, and cooling schemes.
- Optimize conversion efficiency.
- Improve durability and lifetime and lower costs, including for operations and maintenance.
- Develop system-level optimization and control schemes.
- Assess and mitigate moisture content effects on heat transfer and ceramic recession.
- Develop and test hydrogen combustion retrofit packages.
- Enable combustion of carbon-neutral fuels (i.e., NH_3, ethanol vapor).

Though significant progress has been made, additional RDD&D is needed to address issues such as autoignition, flashback, thermoacoustics, mixing requirements, aerothermal heat transfer, materials issues, turndown/combustion dynamics, NO_x emissions, and other combustion-related phenomena. In addition, when hydrogen concentration exceeds 75%, there is a significant change in combustion behavior, requiring new combustor designs, different sensor locations, and new control schemes. These enhancements could allow for limiting NO_x emissions to single-digit (ppm) levels, improved flame detection, and monitoring for flashback and thermoacoustic instabilities. NO_x emissions control while firing hydrogen requires micromixer combustor technology, which is a refinement of today's premixed dilution technologies for low-NO_x natural gas firing. Higher flame temperatures and increased water content could also reduce the lifetime of metal and ceramic parts exposed to hot gases, thereby increasing the need for new materials and thermal barrier coatings, as well as improved cooling schemes.

[64] J. Goldmeer. 2019. Power to Gas: Hydrogen for Power Generation. Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem. GE Power. www.gevernova.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861-Power-to-Gas-Hydrogen-for-Power-Generation.pdf.

Applications



Hydrogen can be used in many applications across multiple sectors, including transportation, power generation, and industrial and manufacturing processes.

Hydrogen has the potential for use in diverse applications across multiple sectors, where it can provide substantial environmental, environmental justice, and economic benefits, as well as improved energy security and resiliency. Large amounts of hydrogen can be used in the transportation, power generation, and industrial and manufacturing sectors, which can enable economies of scale and support a robust domestic supply chain. Integrated energy systems, which can span sectors, offer additional opportunities by using hydrogen as an energy carrier to improve the economics of existing and emerging electric power generation systems.

Transportation

Transportation accounts for a third of U.S. carbon dioxide emissions[65] and can be a key contributor to localized air pollution, which disproportionately impacts disadvantaged communities. In 2023, several Federal agencies collaborated to publish *The U.S. National Blueprint for Transportation Decarbonization*, a landmark interagency framework of strategies and actions to remove all emissions from the transportation sector by 2050. Hydrogen and fuel cells are an important part of a portfolio of options to reduce transportation-related emissions, because they can be used in specific applications that are hard to decarbonize, such as long-haul heavy-duty trucks. Additional examples include medium-duty trucks requiring energy at the job site and ultra-heavy-duty applications such as off-road, rail, and marine applications that require significant onboard energy and longer ranges, involve heavy loads, or demand faster refueling times than may be available with battery-electric alone. With increased urgency to reduce emissions and energy-related expenses, significant opportunities exist, as the medium- and heavy-duty sector accounts for 5% of total vehicles and 21% of transportation emissions.[66]

In addition to its use in fuel cells, hydrogen can also be used directly as a fuel in internal combustion engines or combined with carbon dioxide to produce synthetic fuels, offering even more ways to meet the needs of various transportation applications. These synthetic fuels could allow certain applications or regions to continue using internal combustion engines and the vast existing liquid-fuel infrastructure for hard-to-decarbonize end uses such as long-distance commercial aircraft. Similar to these pathways that utilize hydrogen and carbon dioxide, hydrogen and nitrogen can be used to produce ammonia for use in multiple applications.

Today, hydrogen powers more than 16,000 passenger and commercial vehicles, supplied by more than 50 hydrogen fueling stations nationwide.[67,68] With increased RDD&D, the United States can take up a larger portion of the global fuel cell market, which today includes more than 25,000 fuel cell vehicles and 470 fueling stations

[65] U.S. Department of Energy, U.S. Department of Transportation, U.S. Environmental Protection Agency, and U.S. Department of Housing and Urban Development. 2023. *The U.S. National Blueprint for Transportation Decarbonization*. Washington, D.C.: DOE. DOE/EE-2674. www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf.

[66] Medium- and Heavy-Duty Vehicle action plan will be part of a set of Action Plans that implement the U.S. National Blueprint for Transportation Decarbonization to realize a clean, safe, accessible, affordable, and equitable transportation system. Learn more about other mode-specific action plans. The U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation | Department of Energy

[67] California Fuel Cell Partnership. 2020. "Hydrogen Stations List. Development Status of Hydrogen Stations in California." cafcp.org/sites/default/files/h2_station_list.pdf.

[68] Alternative Fuels Data Center. 2024. "Hydrogen Fueling Station Locations." Accessed Oct. 2, 2024. afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY.

worldwide. An additional transport application is in the forklift and materials handling industry; in the United States, hydrogen powers more than 60,000 forklifts (as of 2023), representing 16% of the total number of forklifts currently employed in the United States.

Besides on-road vehicles, opportunities for hydrogen and hydrogen carriers are also emerging across the transportation sector, including in marine applications. New emissions regulations by the International Maritime Organization limit the sulfur content in fuel oil used on ships (or "bunker fuel") from 3.5% to 0.5%, starting in 2020.[69] These limits are further reduced to 0.1% for ships operating in Emissions Control Areas, including certain coastal regions of the United States and the European Union.[70] Given such increasingly stringent requirements, hydrogen and hydrogen carriers may offer an attractive alternative to bunker fuel. Furthermore, the use of hydrogen in various marine vessels and at ports for drayage trucks, shore power (electricity for ships while docked), and cargo equipment all offer the potential to reduce both carbon dioxide and other emissions and to develop infrastructure in targeted regions.[71] Other emerging opportunities for hydrogen include rail, particularly where the build-out of catenary lines for electrified trains is either impossible or too costly; certain aviation applications where the weight, range, and fueling times of hydrogen systems offer advantages over alternate options like batteries; and off-road transport, such as mining or other applications where hydrogen can allow vehicles to operate with zero emissions in enclosed spaces.

Transportation applications face all the same general challenges outlined in previous sections related to fuel cell cost and durability and hydrogen storage, delivery, and dispensing. The type of infrastructure and associated challenges will be dictated by how hydrogen is stored on the vehicle (or aircraft or vessel)—either as a high-pressure gas, a liquid, or in a hydrogen carrier. Additional challenges include the establishment of necessary supply chains for storage and dispensing components and systems, as well as developing widely accepted refueling protocols covering the full range of transportation options.

Chemical and Industrial Processes

Several industrial and manufacturing processes typically require large volumes of hydrogen, including oil refining and ammonia production.[72] These processes, along with other emerging industrial and chemical uses, are driving economies of scale in the upstream hydrogen supply and associated infrastructure. Steelmaking, in particular, is receiving increasing attention as a source of demand for hydrogen. Steel is the most commonly used metal product worldwide, and the conventional way to produce it involves using coal in blast furnaces to reduce iron ore to iron. Between 7% and 9% of global greenhouse gas emissions are due to steel manufacturing,[73] and by using hydrogen as the primary reducing agent, those emissions can be dramatically reduced. A number of demonstrations of the use of hydrogen in steelmaking are currently underway, including two industrial demonstration projects in Ohio and Mississippi.[74]

[69] The Maritime Executive. 2018. "IMO Answers Questions on the 2020 SOx Regulation." Feb. 3, 2018. www.maritime-executive.com/article/imo-answers-questions-on-the-2020-sox-regulation.

[70] O. Merk. 2014. "Shipping Emissions in Ports." International Transport Forum, Discussion Paper No. 2014-20. www.itf-oecd.org/sites/default/files/docs/dp201420.pdf.

[71] International Energy Agency. 2019. *The Future of Hydrogen: Seizing Today's Opportunities*. www.iea.org/reports/the-future-of-hydrogen; this report provides as one of its main recommendations for governments and industry to "make industrial ports the nerve centres for scaling up the use of clean hydrogen."

[72] According to the International Energy Agency (2019), oil refining and ammonia production use about 69 MMT of hydrogen annually, accounting for a significant percentage of global consumption.

[73] World Steel Association. 2019. "Steel's Contribution to a Low Carbon Future and Climate Resilient Societies." Worldsteel Position Paper. canadiansteel.ca/files/resources/Position_paper_climate_2019_vfinal.pdf.

[74] Office of Clean Energy Demonstrations. 2024. "Industrial Demonstrations Program Selections National Briefing." March 27, 2024. www.energy.gov/sites/default/files/2024-03/FINAL%20IDP%20Selection%20National%20Briefing_0.pdf.

Additional emerging industrial and chemical uses of hydrogen include cement production, which is an energy-intensive process responsible for about 8% of global carbon dioxide emissions,[75] where the use of hydrogen in place of coal could reduce both carbon dioxide and NO_x emissions; synfuel (or "e-fuel") production, which involves reacting carbon dioxide with clean hydrogen, offering an option for versatile net-zero-carbon fuels such as methanol or renewable natural gas; and other industrial processes that use hydrogen as a reducing agent, such as glass manufacturing, or as a hydrogenating agent, such as industrial food processes.

In all these cases, application-specific hydrogen requirements can strongly affect commercial viability. For instance, in steel production, while blast-furnace processes are the current industry standard, the promising alternatives using high concentrations of hydrogen in the reducing agent, such as direct reduction of iron, rely on sufficiently low-cost hydrogen for cost-competitiveness. Across different industrial end uses, the hydrogen cost contribution will depend on process-specific requirements for hydrogen purity, pressure, and other factors that affect production, delivery, and storage costs. Commercial viability will require continued cost reductions in all these areas.

Stationary and Power Generation Applications

Hydrogen can be used in a broad range of stationary power generation applications—including large-scale power generation, distributed power, combined heat and power, and backup power. As noted in the previous section, hydrogen can provide power through electrochemical conversion using fuel cells or through combustion of hydrogen using turbines in simple- or combined-cycle generation.

Fuel cells can efficiently convert hydrogen into power with low emissions, and the inherent modularity of fuel cell systems makes them ideally suited for a broad range of stationary power applications ranging from less than a kilowatt up to the multimegawatt scale. Today, fuel cells are commercially deployed worldwide, providing primary and backup power for industrial facilities, businesses, homes, telecommunications towers, data centers, and more. For example, more than 500 MW of fuel cells have been shipped worldwide for backup power in the United States,[76] primarily for telecommunications towers. Data centers are a notable example of an end use more recently turning to hydrogen-based options. While most data centers today are powered by electricity from the grid (for primary power) and diesel generators (for backup power), major data center operators are exploring the use of hydrogen and fuel cells for reliable and resilient primary and backup power, attracted to benefits such as high efficiency and quiet, emissions-free operation.

Combustion in simple- or combined-cycle power generation is also a viable approach for using hydrogen or hydrogen-rich blends (e.g., blended with natural gas) in a number of stationary applications. As an example, combustion turbines can generate electric power while also providing heat for residential, commercial, and industrial applications. While combustion blends including renewable hydrogen offer the benefits of reduced carbon dioxide emissions, their use in existing distribution infrastructure and combustion equipment poses a number of challenges related to materials compatibility and combustion characteristics. Progress has been made in the modification of natural gas burners in commercially available combustion turbines to accommodate high-hydrogen blends (up to 100% H_2), but continued RDD&D is needed for qualification in utility-scale power generation. Additional RDD&D is also needed to assess the compatibility of hydrogen blends with equipment designed for using natural gas (e.g., building appliances), and to develop separation technologies that can recover high-purity hydrogen from blends for use in applications where pure hydrogen has a higher value.

[75] J. Lehne and F. Preston. 2018. *Making Concrete Change. Innovation in Low-carbon Cement and Concrete*. Chatham House Report. www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf.
[76] Morry Markowitz. 2019. "Fuel cells: Delivering reliable power when needed for emergency response efforts." *Open Access Government*, Dec. 6, 2019. www.openaccessgovernment.org/fuel-cells-reliable-power-emergency-response/79014/.

Integrated Hybrid Energy Systems

Hydrogen also offers a number of opportunities to provide value to the electric power sector through its integration into hybrid energy systems. Broadly defined, a hybrid energy system combines electricity generation, energy storage, and/or energy conversion technologies that are integrated together through an overarching control framework to achieve enhanced capabilities, value, and/or cost savings compared to the stand-alone alternatives, as shown in the example in Figure 17. Hydrogen technologies integrated in a hybrid energy system offer unique benefits in both on-grid and off-grid electric power applications. Examples include mid- to long-duration/seasonal energy storage;[77] grid leveling and stabilization services that leverage the fast-acting dynamic response of electrolyzers;[78] and the ability to coproduce (along with electricity) hydrogen or other hydrogen-based fuels, chemicals, or products for use in diverse markets, potentially at higher value than electricity.[79] Multiple hybrid scenarios are being explored that could optimally leverage the benefits of integrated energy systems; some key examples are described below.

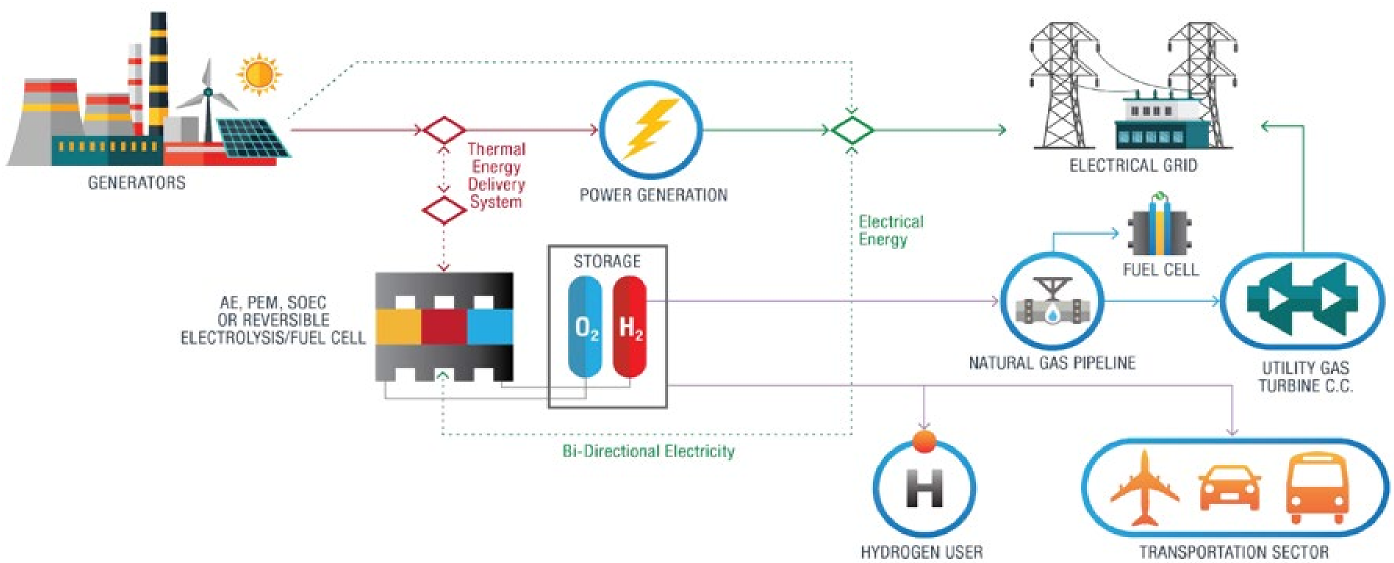


Figure 17. Example hybrid hydrogen energy system[80]

Grid Integration and Renewable Hybrid Systems

As the electric grid evolves with higher penetrations of variable renewable energy sources, grid-integrated electrolyzers can provide energy storage and other grid services to improve reliability and resiliency. Hydrogen produced via electrolysis can be used as a means of bidirectional energy storage, where it is converted on demand back to electricity through low-emissions power generation technologies such as fuel cells or combustion turbines. It can also be used in one-way chemical energy applications, such as through injection into the natural gas pipeline infrastructure, or through on-site coproduction of value-added commodities such as ammonia or methanol. Ancillary grid services including voltage and frequency stabilization are enabled by the rapid (sub-second) dynamic response times of electrolyzers, which have been validated through national laboratory projects that simulate responses to grid fluctuations.[81] Techno-economic analysis is being conducted, in collaboration with electric utilities, to identify optimal configurations for integrating electrolyzers with renewables in grid, microgrid,

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[77] C. Hunter, E. Reznicek, M. Penev, J. Eichman, and S. Baldwin. 2020. “Energy Storage Analysis.” Presented at the DOE Hydrogen and Fuel Cells Program 2020 Annual Merit Review and Peer Evaluation Meeting, 21 May 2020. www.hydrogen.energy.gov/pdfs/review20/sa173_hunter_2020_o.pdf.

[78] J. Kurtz, K. Harrison, R. Hovsapian, and M. Mohanpurkar. 2017. “Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TV031.” Presented at the DOE Hydrogen Program 2017 Annual Merit Review, 8 June 2017. www.hydrogen.energy.gov/pdfs/review17/tv031_hovsapian_2017_o.pdf.

[79] Ruth et al. 2020. The Technical and Economic Potential of the H2@Scale Concept.

[80] Idaho National Laboratory, National Energy Technology Laboratory, and National Renewable Energy Laboratory. 2019. “Applied Energy Tri-Lab Consortium.” Internal DOE presentation.

[81] R. Hovsapian, J. Kurtz, M. Panwar, A. Medam, and C. Hanson. 2019. “Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TA015.” Presented at the 2019 DOE Hydrogen and Fuel Cells Program Annual Merit Review, 29 April 2019. www.hydrogen.energy.gov/pdfs/review19/ta015_hovsapian_2019_o.pdf.

and off-grid applications.[82] In addition to analysis, modeling tools and reference designs are being developed for gigawatt-scale, off-grid, tightly coupled hybrid energy systems. These site-specific, optimized system designs will help show how purpose-built energy systems, with renewable H_2 production co-located with industry end uses, can provide alternative pathways and accelerate the path to decarbonization for hard-to-abate industries.

Fossil Energy Hybrid Systems

Hybrid energy systems integrating natural gas or coal conversion with hydrogen technologies can provide significant value for industrial applications. Pilot-scale plants have been deployed that integrate systems for SMR of natural gas with vacuum-swing adsorption to coproduce hydrogen for petroleum refining along with concentrated carbon dioxide for use in enhanced oil recovery. Large-scale gasification facilities that co-fire coal, biomass, and waste plastics can be integrated with thermal storage, hydrogen production and utilization technologies, and carbon capture to achieve low-emissions power generation. The use of optimized CCUS along with the co-firing of biomass in these facilities offers a potential pathway to carbon-negative power generation. Also under development are polygeneration systems that use high-temperature fuel cell technologies to efficiently convert natural gas or gasified coal/biomass/waste into electricity, heat, and hydrogen with low emissions. Ongoing RDD&D in fossil-based hybrid systems is needed to improve integration optimization and enable scalability, affordability, and energy security.

Nuclear Hybrid Systems

There is growing interest in integrating hydrogen production at nuclear power plants as a means to enhance load-following capabilities, utilize unused energy, and provide an additional revenue stream. For example, a 1-GW nuclear power plant can produce about 54,000 tonnes of hydrogen in a year using high-temperature electrolysis (e.g., for direct sale or use in synthetic fuel production as a value add), assuming the plant produces electricity for 70% of the time and hydrogen for 26% of the time (with 4% downtime for maintenance).[83] Leveraging nuclear-generated electricity and heat, hydrogen can be efficiently produced using low- or high-temperature electrolyzer technologies, and utilized on-site to service hydrogen needs of the nuclear plant (e.g., in turbine generator cooling) or exported/monetized for other end uses. Nuclear hybrid systems are ready for full-scale commercial deployment, as pilot projects currently underway at existing nuclear plants are expected to rapidly resolve many remaining uncertainties, accelerating their availability for full-scale implementation. In addition, DOE-led risk assessments pave the way toward regulatory approvals and techno-economic analysis—including market assessments for a number of specific nuclear power plants. These have identified the potential economic benefits of producing hydrogen through different on-site electrolyzer options, including those currently being pursued via pilot projects and other technologies. Along with the continued development of both low- and high-temperature electrolyzers, cost reductions will result from scale-up of electrolyzer manufacturing and integrating electrolyzers behind the meter at nuclear power plants. While advanced nuclear plants will cost more than the current fleet of reactors, the high-capacity factor for nuclear power provides an important economic advantage that helps to mitigate their higher cost.

[82] J. Eichman, O.J. Guerra, M. Koleva, and B. McLaughlin. 2019. "PG&E H2@Scale CRADA: Optimizing an Integrated Solar-Electrolysis System." National Renewable Energy Laboratory, 5 Nov. 2019. www.hydrogen.energy.gov/pdfs/htac_nov19_06_eichman.pdf.

[83] Assumes an electrolyzer electrical conversion efficiency of 40 kWh/kg, consistent with the state of the art in polymer electrolyte membrane electrolysis, as documented in D. Peterson, J. Vickers, and D. DeSantis. 2020. "Hydrogen Production Cost From PEM Electrolysis - 2019." DOE Hydrogen and Fuel Cells Program Record 19009. www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf. Calculation: (1,000,000 kW × 8,760 hours/yr × 26%) / 42 kWh/kg = 54,228,571 kg/yr = approximately 54,228 tonnes/yr.

The Regional Clean Hydrogen Hubs

The Bipartisan Infrastructure Law authorized $8 billion to establish the Regional Clean Hydrogen Hubs Program (H2Hubs)[84] to create networks of hydrogen producers, consumers, and local connective infrastructure to accelerate the use of hydrogen as a clean energy carrier. The H2Hubs will form the foundation of a national clean hydrogen network that could contribute substantially to decarbonizing multiple sectors of the economy, including electric power generation, heavy-duty transportation, and industrial processes like steel and ammonia production, while maximizing benefits to local communities through community benefits plans.

Matching the scale-up of clean hydrogen production to a growing regional demand is a key pathway to achieving large-scale, commercially viable hydrogen ecosystems. The H2Hubs will enable this pathway by demonstrating low-carbon-intensity and economically viable hydrogen-based energy ecosystems that can replace existing carbon-intensive processes.

Seven H2Hubs, representing $7 billion in DOE investment, form the foundation of the DOE Clean Hydrogen Hubs Program and are illustrated in Figure 18.[85] More information about the selected hubs and the current status can be found at www.energy.gov/oced/regional-clean-hydrogen-hubs.

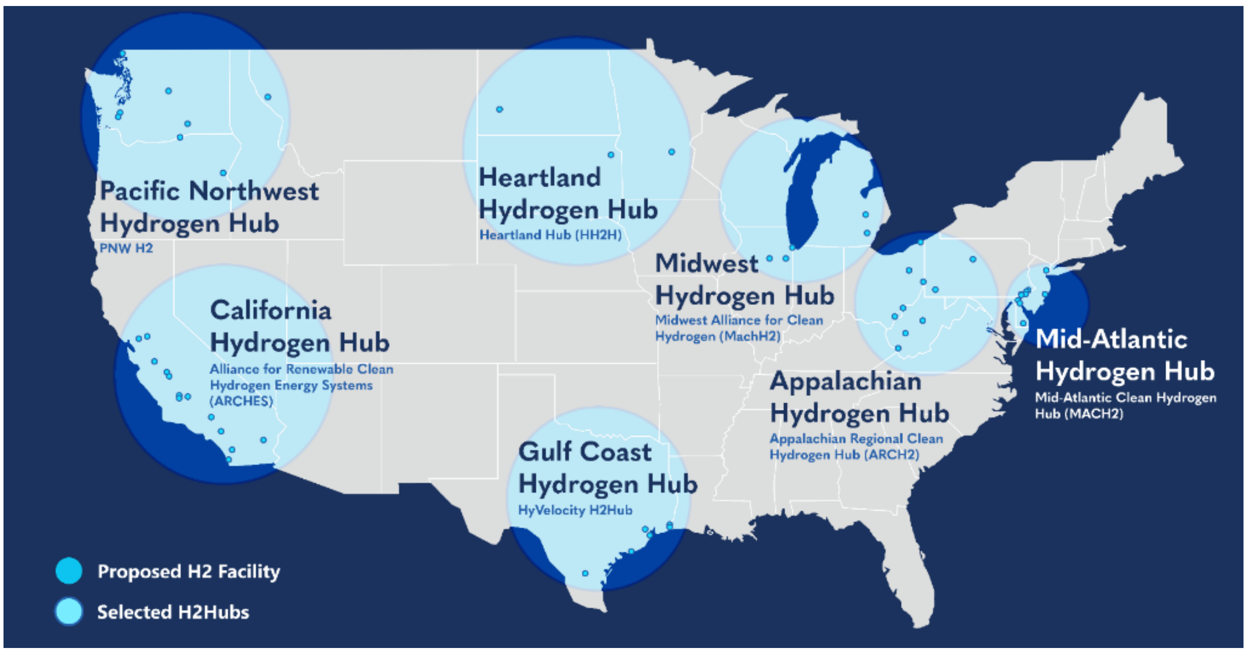


Figure 18. Selected H2Hubs

As part of the Regional Clean Hydrogen Hubs Program, DOE announced a demand-side support program designed to accelerate commercialization and demonstrate the production, processing, delivery, storage, and end use of clean hydrogen at the H2Hubs. A DOE-supported consortium will help accelerate commercial liftoff of the clean hydrogen economy and support the launch of the H2Hubs.[86] DOE will work with the consortium and the H2Hubs to design robust demand-side support measures that will facilitate purchases of clean hydrogen produced by H2Hub-affiliated projects to reduce climate pollution, create good jobs, support clean air, and advance U.S. competitiveness in various end-use sectors, including energy-intensive industry and heavy-duty transportation.

The production, processing, delivery, storage, and end use of clean hydrogen, including innovative uses in the industrial sector, are crucial to DOE's strategy for achieving our nation's climate goal of a 100% clean electrical grid by 2035 and net-zero-carbon emissions by 2050.

[84] Office of Clean Energy Demonstrations. 2024. "Regional Clean Hydrogen Hubs." Accessed Oct. 3, 2024. www.energy.gov/oced/regional-clean-hydrogen-hubs-0.
[85] U.S. Department of Energy. 2023. "Biden-Harris Administration."
[86] Office of Clean Energy Demonstrations. 2024. "DOE Selects Consortium to Bridge Early Demand for Clean Hydrogen, Providing Market Certainty and Unlocking Private Sector Investment." Jan. 17, 2024. www.energy.gov/oced/articles/doe-selects-consortium-bridge-early-demand-clean-hydrogen-providing-market-certainty.

Crosscutting Challenges and Opportunities

Affordable hydrogen at industrial scales is essential to many diverse applications and end uses, both current and emerging. While cost challenges are being addressed through ongoing RDD&D across hydrogen production, delivery, storage, and conversion technologies, additional efforts to address important crosscutting issues related to technology scale-up, manufacturing and supply chains, and cybersecurity, as well as hydrogen safety, codes, and standards, are also key for achieving the economies of scale and widespread adoption envisioned in H2@Scale.

Manufacturing

For hydrogen to transition from niche applications to mass markets, it will be essential to develop industrial-scale techniques, processes, and facilities for manufacturing hydrogen-related technology components and systems at large volumes. A robust domestic supply chain could also ensure the United States stays at the forefront of this emerging global industry. While the bulk of the investment needed to build manufacturing capacity will fall to industry—as incentivized by growing market demands—RDD&D efforts will be needed to overcome technical challenges and accelerate progress.

By developing processes and technologies specifically tailored to high-volume manufacturing, RDD&D efforts can help achieve economies of scale in manufacturing. These efforts can also lead to additional technology and systems integration improvements, resulting in even greater cost reductions. Key opportunities for crosscutting advances include developing:

- High-speed manufacturing techniques for processes such as forming, stamping, molding, sealing, joining, coating, and roll-to-roll processing.
- Best practices for material and component handling.
- Additive and automated manufacturing/assembly processes.
- Technologies for in-line diagnostics and quality control/quality assurance.
- Sensors and other technologies to reduce manufacturing defects in high-throughput production.
- Manufacturing processes and technology designs that enable efficient recycling/upcycling, especially of critical materials.

Standardized designs for systems and components are also needed to unify specifications among system and component providers, which simplifies technology development and lowers supplier costs.

Safety, Codes, and Standards

Technically sound codes and standards, effective safety- and quality-related technologies and processes, and widely disseminated safety information will play a key role in realizing the H2@Scale vision. They are essential for deploying hydrogen-related technologies; ensuring quality, consistency, and interoperability; and providing regulatory bodies, manufacturers, system operators, and end users with the tools they need to ensure that emerging technologies are at least as reliable, safe, and high-performing than the incumbents. They also improve confidence in the commercial viability of the technologies among all stakeholders, which can further accelerate adoption and encourage investment.

The continued development and revision of codes and standards will require ongoing research and data to improve understanding of the physical and chemical properties of hydrogen. Close coordination and collaboration with code and standard development organizations will continue to be essential to ensure research efforts are properly aligned with the needs of stakeholders. And in order to ensure a robust and competitive global supply chain for hydrogen and related technologies, key codes and standards—such as refueling protocols—will need to be internationally harmonized.

RDD&D efforts will be needed to improve hydrogen sensing and contaminant detection, and development of quantitative risk assessment tools and streamlined permitting processes will help with siting hydrogen infrastructure and further reduce barriers to deployment. Risk mitigation strategies, best safety practices, and lessons learned must be identified and evaluated, and ongoing support will be needed to develop and sustain collaborative institutional processes for disseminating safety information.

Hydrogen codes and standards are in use today and are critical in current industrial-scale hydrogen technologies (e.g., reforming, coal gasification, refineries), as are safety technologies such as sensors for monitoring and control at industrial plants and refineries. As new applications emerge—such as marine, rail, and heavy-duty vehicles—additional efforts in all aspects of safety, codes, and standards may be required to address needs specific to each application.

Environmental Justice and Workforce Development

Environmental justice activities are integrated across DOE’s Hydrogen Program and are critical to successfully reaching the H2@Scale vision. Prioritizing early, frequent, and meaningful community engagement; listening to and addressing environmental justice concerns; and focusing on the production methods and end uses that will most reduce disproportionate public health impacts of the energy system on disadvantaged communities are vital ways to ensure the transition to the hydrogen economy is just. Liftoff of the hydrogen economy also creates the opportunity to support a skilled workforce and union jobs across a range of sectors, including workers transitioning from fossil energy employment and for individuals denied access to high-quality employment. Realizing these opportunities will similarly require continued research and analysis to understand priority jobs across regions, the current status of workforce training programs and gaps, the adequacy of workforce safety requirements, and effective mechanisms to deploy new training programs.

Additional efforts will be needed to develop community-driven metrics to measure efficacy and impacts of hydrogen technologies on environmental justice communities. Collaboration with unions and other labor stakeholders will be required to create and expand registered apprenticeship and certification programs for hydrogen-related jobs. More research is needed to assess the impacts of the hydrogen economy on regional water supplies and local air quality. Equitable community engagement best practices and lessons learned must be identified and evaluated, and ongoing support will be needed to facilitate two-way engagement.

Communities and workers are impacted by the hydrogen economy today. As the economy scales, additional work in all dimensions of workforce development and environmental justice will be required to address the concerns and needs around hydrogen technologies’ applications.

Common RDD&D Thrusts for Hydrogen and Related Technology Applications

- Development of rigorous application-specific targets for hydrogen utilization.
- Materials compatibility issues in diverse end uses.
- Reduced cost and improved durability and efficiency in industrial-scale electrolyzers, fuel cell systems, combustion turbines and engines, and hybrid systems.
- Component- and system-level integration and optimization, including balance-of-plant components and systems.
- Optimized controls of integrated systems, including cybersecurity.
- Manufacturing and scale-up, including process intensification.
- Harmonized codes and standards, including refueling protocols.
- Capacity expansion models to identify value propositions for use of hydrogen in new applications.

4 Program Execution and Collaboration

Program Execution

Stakeholder Input

To maintain alignment with the priorities of key stakeholders—including industry, end users, academia, the investment community, and other government agencies—the Hydrogen Program actively solicits input to incorporate in the planning of its activities. Separately, federally recognized Indian Tribes and Alaska Native Claims Settlement Act Corporations will be key partners and whose consultation and engagement will be guided by DOE 144.1 Policy and Order on Tribal Consultation and Engagement. Among the primary channels for this input are *requests for information* and *workshops* conducted by DOE to help establish high-level program direction and to develop and update technology-specific RDD&D plans. The Hydrogen Program also regularly conducts workshops for specific technology areas to identify and update RDD&D priorities, develop plans, and identify technical targets and milestones. These workshops involve a wide range of stakeholders and provide an open forum for discussion of the status of the technologies and the challenges facing their development and deployment. Results from these activities feed into the development of DOE strategies and funding plans.

Program Funding

The Hydrogen Program's activities are funded using various competitive mechanisms, including *notices of funding opportunities* (NOFOs),[87] through which industry, university, national laboratory, and other private sector projects are selected. Several offices also issue separate *lab calls* to make selections for national laboratory projects. The Program uses *cooperative research and development agreements* to encourage partnerships between the private sector and national labs for joint development and *strategic partnership projects* [88] through which industry can contract company-specific tasks to be conducted at national labs.

DOE has had the authority to invest more than $20 billion over the last two decades, including more than $9.5 billion through the Bipartisan Infrastructure Law, in various areas from hydrogen production through end use, including the recently announced H2Hubs. Through these and ongoing programs, all DOE offices use competitive NOFO and related processes to engage a diverse set of stakeholders across industry, academia, and national labs through rigorous, merit-based review processes.

Measures To Ensure Effectiveness

The Hydrogen Program employs a number of program management processes to ensure the effective use of taxpayer funds, including:

- *Developing targets and milestones* for all R&D pathways in close consultation with experts in industry, end users and customers, communities, and the scientific research community.

[87] Formerly known as "funding opportunity announcements" throughout DOE.
[88] Formerly known as "work for others" throughout DOE.

- *A rigorous, competitive selection process*, which ensures projects are selected based on technical feasibility, high-impact potential, innovation, and the likelihood of making progress toward DOE's milestones and targets.
- *External review and evaluation processes*, which include program reviews by the National Academies, reviews of DOE's research, development, and demonstration (RD&D) progress under the partnership with U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability; see more in "Private Sector and Other Nongovernmental Partnerships"); other government agencies, congressionally requested reviews,[89,90] and comprehensive project reviews by more than 200 technical experts at the Program's Annual Merit Review and Peer Evaluation Meeting.[91]
- *Downselection and go/no-go decisions*, which entail a systematic process for discontinuing certain research pathways via "go/no-go" decision points defined by performance-based milestones and quantitative metrics at the sub-program, task area, and project level. For example, the program has discontinued R&D of onboard vehicular fuel processing, sodium borohydride hydrolysis, and carbon nanotubes for onboard vehicular hydrogen storage.

Internal and External Coordination and Collaboration

Internal Organization

While DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) within EERE has had the lead role in coordinating hydrogen-related activities across DOE for more than two decades, multiple offices are engaged either directly or indirectly in hydrogen-related activities. Figure 19 shows the key offices involved: EERE, FECM, NE, OE, SC, LPO, MESC, OCED, and ARPA-E. The Hydrogen and Fuel Cells Joint Strategy Team coordinates Hydrogen Program activities among the DOE offices and meets regularly at a technical level to evaluate the progress of activities with regard to milestones and performance goals; strengthen information exchange on programmatic and technical developments; provide recommendations for improving management practices and technical performance; and collaborate on systems analysis activities to gain understanding of the impacts of alternative technology pathways from environmental, energy, and economic standpoints.

The participating offices manage their respective NOFO processes and project execution through both their field offices and procurement functions and, in some instances, direct projects at national laboratories. The offices coordinate on NOFO topics, merit reviews, and project reviews to avoid duplication and ensure an optimal and cohesive strategy to tackle the challenges in enabling the successful commercial viability of hydrogen and related technologies. Examples of key activities and core mission space within each of these offices is shown in Table 2.

The Hydrogen Program also coordinates with crosscutting offices including the Arctic Energy Office, Office of Energy Justice and Equity, Office of International Affairs, Office of Indian Energy Policy and Programs, Office of Policy, and Office of Technology Transitions.

- The Arctic Energy Office (AE) is the only regionally focused office in DOE. The office advises DOE's leadership, offices, and workforce on Arctic energy, science, and national security. AE coordinates efforts across DOE to ensure a unified voice and action. To achieve its mission, AE makes connections between Alaskan residents, companies, Alaska Native Corporations and Villages, academic institutions, national labs, interagency partners, and other stakeholders to support energy solutions, invest in workforce development, and share Arctic expertise and analysis.

[89] U.S. Department of Energy. 2019. *Report on the Status of the Solid Oxide Fuel Cell Program*. Report to Congress. www.energy.gov/sites/prod/files/2019/09/f66/EXEC-2019-002655_Signed%20Report%201.pdf.
[90] U.S. Department of Energy Hydrogen Program. 2024. "DOE Biennial Reports to Congress." Accessed Oct. 3, 2024. www.hydrogen.energy.gov/htac_reports.html.
[91] U.S. Department of Energy Hydrogen Program. 2024. "Annual Merit Review and Peer Evaluation." Accessed Oct. 3, 2024. www.hydrogen.energy.gov/annual_review.html.

- The Office of Energy Justice and Equity (EJE) develops and executes DOE-wide policies to implement applicable legislation and executive orders that strengthen diversity and inclusion goals affecting equal employment opportunities, small and disadvantaged businesses, minority educational institutions, and historically underrepresented communities. EJE's mission is to identify and implement ways of ensuring that everyone is afforded an opportunity to participate fully in DOE's programs, opportunities, and resources.
- The Office of International Affairs (IA) works with the larger U.S. interagency foreign policy team to collaborate with governments worldwide to design and accelerate global clean energy transitions that address the climate crisis, enhance and ensure energy security, and create good-paying jobs and prosperity for the American people and communities everywhere. IA leads more than two dozen bilateral and regional energy dialogues, partnerships, councils, and other forums to help countries achieve their energy security, energy access, and climate goals. Through high-level diplomacy and mobilization of world-class technical expertise—including through the 17 DOE National Labs—IA is helping to solve some of the world's most complex energy challenges, especially in emerging economies, at a time when geopolitical conflicts are stressing energy markets.
- The Office of Indian Energy Policy and Programs (IE) is authorized to fund and implement a variety of programs and projects that promote Tribal energy development, efficiency, and use; reduce or stabilize energy costs; enhance and strengthen Tribal energy and economic infrastructure; and electrify Indian lands and homes.
- The Office of Policy (OP) supports the Secretary of Energy, Deputy Secretary, Under Secretaries, and the entire Department of Energy, providing analysis on domestic energy policy and related integration of energy systems. Its work spans technology policy, deployment, and infrastructure; state, local, Tribal, and territorial policy; and energy jobs. It provides expertise in electricity systems, buildings and industry, mobility, energy security, and all parts of the transition to a clean energy economy for all. Working in coordination with the White House, Congress, other Federal agencies, and local stakeholders, OP aims to facilitate the transition to a zero-emissions, equitable, and secure energy economy.
- The Office of Technology Transitions (OTT), established in 2015, focuses on enabling technology transfer and expanding the commercial impact of DOE's RDD&D portfolio to advance the economic, energy, and national security interests of the nation. OTT develops DOE's vision for expanding the commercial impact of its research investments and streamlines information and access to DOE's National Labs to foster partnerships that move innovations from the labs into the marketplace. OTT also coordinates DOE's Technology Commercialization Fund, which leverages funding from the applied energy programs to mature, promising energy technologies with the potential for high impact.

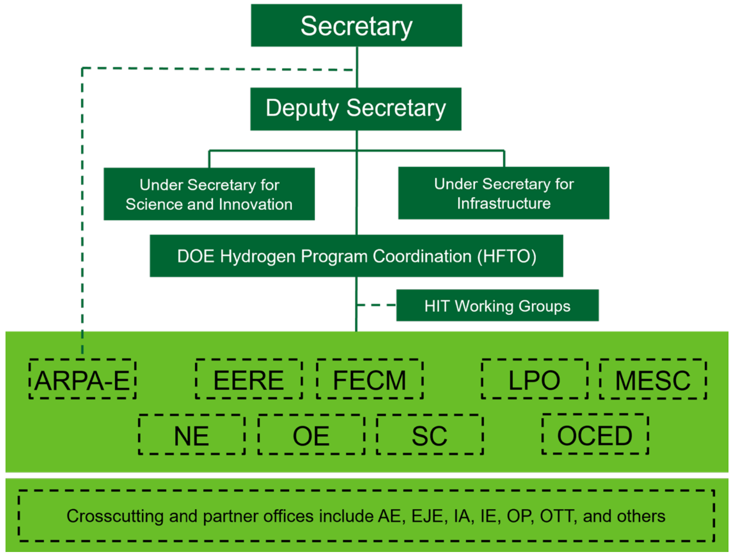


Figure 19. DOE Hydrogen Program organizational structure

In addition, the Hydrogen Program coordinates with crosscutting initiatives and efforts that span multiple offices across DOE, including the Hydrogen Shot, the first of DOE's Energy Earthshots™, which was launched in June 2021 with an ambitious goal to reduce the cost to producing clean hydrogen by 80% to $1 per kilogram in 1 decade ("1 1 1"). The Energy Earthshots initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions. If the Hydrogen Shot goals are achieved, analysis shows that there is an opportunity for at least a fivefold increase in clean hydrogen use.

Table 2. Offices Engaged in the DOE Hydrogen Program: Key Activities and Focus Areas

Office of Energy Efficiency and Renewable Energy
EERE leads a comprehensive strategy focusing on RD&D and innovations across a broad portfolio of renewable energy technologies, energy efficiency in buildings and the industrial sector, transportation technologies across applications (vehicles, trucks, marine, rail, and air), advanced manufacturing, industrial decarbonization, and crosscutting activities. EERE comprises several offices, many of which play a role in advancing hydrogen and fuel cell technologies. Examples include: • **HFTO** leads DOE's Hydrogen Program and leads critical initiatives like the Hydrogen Shot and H2@Scale. HFTO supports RD&D to advance diverse technologies for hydrogen production, delivery, storage, and utilization. HFTO emphasizes RD&D at the materials, component, and system levels to address the cost, performance, durability, and safety requirements for widespread adoption of hydrogen across the transportation, industrial, and stationary power sectors. RD&D focus areas include electrolyzers and other advanced water-splitting approaches; advanced liquefaction and carriers for hydrogen delivery; advanced high-pressure tanks, liquid hydrogen storage, and material-based storage systems; and low- and medium-temperature fuel cells. HFTO coordinates with FECM on various topics including reversible SOFCs and carbon-negative hydrogen production; with NE and OE on integrating renewables into the grid using hydrogen as an energy storage medium; with FECM and ARPA-E on hydrogen sensing; and with SC and ARPA-E on basic science and next-generation technologies. • The **Advanced Materials and Manufacturing Technologies Office** supports manufacturing innovations—such as roll-to-roll manufacturing, 3D printing, and carbon fiber production—to reduce cost and enable a competitive domestic supply chain for technologies such as electrolyzers, hydrogen storage tanks, and fuel cells. The office also supports technical assistance activities enabling the use of fuel cells in combined heat and power systems for industrial and building applications. • The **Industrial Efficiency and Decarbonization Office** accelerates the innovation and adoption of cost-effective technologies that eliminate industrial greenhouse gas emissions, including through the use of clean hydrogen to help decarbonize applications such as the production of steel and concrete, as well as ammonia synthesis. • The **Wind Energy Technologies Office** invests in RD&D innovations to advance offshore, land-based, and distributed wind systems. The office's efforts include modeling and demonstration of hybrid energy systems integrating wind power with electrolysis for clean hydrogen production and utilization. • The **Bioenergy Technologies Office** supports a wide range of RD&D, including technologies that can utilize hydrogen for production of biofuels and bioproducts. The office's efforts also enable hydrogen production from biomass or biowaste streams through various approaches, including the use of advanced electrochemical and microbial processes.

- The **Solar Energy Technologies Office** accelerates the advancement and deployment of solar technology in support of an equitable transition to a decarbonized economy. The office's efforts include solar-assisted thermal and electrochemical splitting of water for clean hydrogen production.
- The **Water Power Technologies Office** enables research, development, and testing of new technologies to advance marine energy, as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid. In its portfolio, the office supports projects that explore the integration of hydrogen and fuel cell technologies with hydropower to enhance grid resilience.
- The **Geothermal Technologies Office** works to reduce costs and risks associated with geothermal development by supporting innovative technologies that address key exploration and operational challenges. The office's RD&D is synergistic with subsurface hydrogen storage, as well as geologic hydrogen generation.
- The **Building Technologies Office** supports RD&D to accelerate the adoption of cost-effective technologies, techniques, tools, and services that enable high-performing, energy-efficient, and demand-flexible residential and commercial buildings. The office's RD&D is synergistic with combined heat and power using clean hydrogen.
- The **Vehicle Technologies Office** supports a broad portfolio of next-generation technologies to improve battery-electric and other alternative fuel vehicles, advanced combustion engines, and overall vehicle efficiency improvements (e.g., lightweighting). The office also manages the Energy Efficient Mobility Systems Program, which examines the systemic energy impacts of connected and automated vehicles, where hydrogen and fuel cells have a potential role, particularly for freight.

Office of Fossil Energy and Carbon Management

FECM seeks to advance transformative science and innovative technologies that enable the reliable, efficient, affordable, and environmentally sound use of fossil fuels. The office conducts diverse RD&D efforts, including advanced power generation; power plant efficiency; water management; CCUS technologies; executing natural gas regulatory responsibilities; and technological solutions for the prudent and sustainable development of unconventional oil and gas domestic resources. Two major FECM programs are currently conducting fossil-energy-based hydrogen RD&D:

- The **Office of Carbon Management** is focused on advancing technologies for producing clean hydrogen from carbon-containing feedstocks with CCUS, including through modular gasification systems and co-gasification with sustainably sourced biomass, municipal solid waste, and/or unrecyclable waste plastics. Key priorities are hydrogen combustion turbines and reversible solid oxide cell systems for large-scale power generation, as well as integration with gasification islands for large chemical coproduction (e.g., ammonia and polygeneration). Reversible solid oxide cell R&D is conducted in coordination with EERE's HFTO to ensure there is no duplication of efforts. FECM will also coordinate with EERE, NE, and other offices on hybrid energy systems where reversible solid oxide cells can be integrated. RD&D emphasis includes combustion and fuel science, catalysis, gasification, separations, and CCUS to enable the utilization of carbon-neutral (or even carbon-negative when co-feeding biomass) hydrogen at scale. In addition, the office will evaluate the use of hydrogen in energy storage systems and technologies for storing large volumes (>1,000 tons) on-site. Such volumes could be used for dispatchable, long-duration energy storage for grid support. Finally, carbon dioxide utilization programs will require hydrogen for the manufacture of polymers, chemicals, and other products that will support both manufacturing and reduction of carbon dioxide emissions.
- The **Office of Resource Sustainability** administers DOE's technological development and approaches for reducing the environmental impacts of the historical and continued use of fossil fuels. The office and its Natural Gas Decarbonization and Hydrogen Technologies Program leverage insight and RD&D expertise in oil and natural gas production, transport, storage, and distribution to enable the use of natural gas resources and infrastructure in support of a clean hydrogen economy. The Natural Gas Decarbonization and Hydrogen Technologies Program and its partners develop technologies for low-carbon-intensity hydrogen production; the safe and efficient distribution of hydrogen blends within natural gas infrastructure; and the development of underground hydrogen storage technologies. Specific RDD&D areas of interest include (1) novel natural gas conversion processes such as catalytic methane pyrolysis to produce clean hydrogen and solid carbon products, (2) developing highly sensitive sensor technologies for real-time hydrogen monitoring within natural gas infrastructure and (3) enabling research and technology outcomes to demonstrate bulk subsurface storage.
- FECM also leads DOE's CCUS efforts and collaborates with EERE on opportunities to co-locate hydrogen production with CCUS sites and large-scale hydrogen storage sites to enable the use of hydrogen and carbon dioxide to produce synthetic chemicals and fuels.

Office of Nuclear Energy

NE works to advance nuclear power to meet the nation's energy supply, environmental, and national security needs. RD&D objectives include enhancing the long-term viability and competitiveness of the existing U.S. reactor fleet and developing advanced nuclear reactor technologies. As part of these efforts, NE is working with partners in EERE and industry to conduct RD&D to enable commercial-scale hydrogen production using heat and electricity from nuclear energy systems. In addition to emissions-free electricity, nuclear reactors produce large amounts of heat, which can be used to improve the economics of hydrogen production. NE's efforts related to hydrogen production include:

- NE and EERE have collaboratively initiated demonstration of both high-temperature and low-temperature electrolysis systems at operating light-water reactors that can provide reliable, low-cost heat and electricity necessary to produce hydrogen economically.

NE, in coordination with industry, utilities, and vendors, is also developing the necessary control systems to readily apportion energy and electricity based on market demands.

- Modeling, simulation, and experimentation to develop and advance technologies needed to integrate hydrogen production methods with existing and future reactors in ways that optimize economic performance as they operate in concert with other generation sources and grid loads.
- Development of advanced reactors that will operate at very high temperatures, making them well suited for promising new thermally driven hydrogen production processes. These advanced reactors are now being developed by NE through directed laboratory R&D, university programs, and private-public partnerships with domestic nuclear industry vendors.
- NE is developing probabilistic risk assessments and hazards analysis for siting electrolysis units near nuclear reactors. These studies will help inform regulatory processes and reduce the time to commission and operate co-located electrolysis units.
- NE is conducting front-end engineering and design studies to scale up electrolysis to 500 MW at nuclear plants.

Office of Electricity

OE leads DOE's research, development, and demonstration programs to strengthen and modernize the nation's power grid. Working with public and private partners, OE prioritizes resilient, reliable, secure, and affordable clean electricity across the nation. During a time of historical transformation for the nation's electrical grid, OE targets national challenges through three collaborative divisions:

- **Grid Systems and Components** pursues next-generation technologies, tools, and techniques for the electricity delivery system—from hardware components and associated software to integrated grid systems.
- **Grid Controls and Communications** aims to modernize the nation's electricity delivery system through secure communications, controls, and protection systems, securing critical infrastructure and American lives through the safe and reliable delivery of electricity amidst increasingly high-impact threats.
- **Energy Storage** drives DOE's efforts to rapidly deploy technologies commercially and expedite grid-scale energy storage in meeting future grid demands with safe, low-cost, and earth-abundant resources for cost-effective, grid-scale, and long-duration energy storage.

OE is strongly engaged in several crosscutting collaborative initiatives, including the Energy Storage Grand Challenge, the Long Duration Storage Shot™, and the Grid Modernization Initiative. OE collaborates with the Hydrogen Program on hydrogen-related RD&D, particularly with respect to long-duration energy storage and industrial or infrastructure electrification. Other relevant areas of interest include power electronics to enable cost reductions for a range of technologies such as electrolyzers; energy storage safety; techno-economic analysis of storage systems; and assessing the impacts of RDD&D progress, varying grid markets, and regional markets for hydrogen.

Office of Science

The mission of DOE's **SC** is to deliver scientific discoveries and major scientific tools to transform our understanding of nature and advance the energy, economic, and national security of the United States. The Office of **Basic Energy Sciences** within SC supports fundamental research addressing critical challenges related to hydrogen storage, production, utilization, and conversion. These efforts, which include work conducted by the Energy Earthshot Research Centers, the Science Foundations for the Energy Earthshots projects, and the Energy Frontier Research Centers, complement the technology-specific RDD&D supported by other DOE offices and provide foundational knowledge that can bring advances to many areas of technology development.

Recent advances offer exciting new research opportunities for addressing both short-term and long-term challenges for hydrogen and related technologies. These include advances in synthesis, catalysis, modeling, artificial intelligence/machine learning, analytical instrumentation at user facilities, high-performance computing, and bio-inspired approaches. Priority research opportunities identified by a recent Basic Energy Sciences Roundtable on Foundational Science for Carbon-Neutral Hydrogen Technologies include: (1) discover and control materials and chemical processes to revolutionize electrolysis systems; (2) manipulate hydrogen interactions to harness the full potential of hydrogen as a fuel; (3) elucidate the structure, evolution, and chemistry of complex interfaces for energy efficiency and atom efficiency; and (4) understand and limit degradation processes to enhance the durability of hydrogen systems. Examples of key basic research focus areas supporting these priorities include:

- Novel materials for hydrogen storage.
- Membranes for separation.
- Purification.
- Ion transport.
- Design of catalysts at the nanoscale.
- Bio-inspired materials and processes.
- Solar hydrogen production.

Loan Programs Office

LPO provides loans and loan guarantees to finance and de-risk high-impact, commercial-scale projects that will help the United States reach its decarbonization goals. Over the past decade, LPO has closed more than $30 billion across innovative clean energy, advanced transportation, and Tribal energy projects. LPO serves as a bridge to bankability for first-of-a-kind deployments in order to render the project or underlying technology ready for commercial financing on the next deployment. LPO has issued two conditional loan guarantees in the clean hydrogen space that produce hydrogen via electrolysis and methane pyrolysis, respectively: Plug Power ($1.66 billion, May 2024)[92] and Monolith ($1.04 billion, December 2021).[93] The ACES Delta project, which represents a $504.4 million loan guarantee, reached financial close in June 2022.

Office of Manufacturing and Energy Supply Chains

MESC is dedicated to enhancing U.S. manufacturing capabilities and securing resilient supply chains for energy technologies. MESC serves as the front line of clean energy capital deployment to accelerate America's transition to a resilient, equitable energy future via more than $20 billion of direct investment in manufacturing capacity and workforce development. MESC focuses on strengthening and securing supply chains needed to modernize the nation's energy infrastructure, supporting workforce education and training, and providing robust manufacturing modeling to guide and support investments and policy recommendations. MESC operates in late-stage technology development, driving large-scale deployment of new technologies including the manufacturing of electrolyzers and fuel cells. Focused programs in electrolyzers and fuel cells are:

- U.S. Domestic Manufacturing Conversion Grants.
- The Qualifying Advanced Energy Project Credit (48C).

Office of Clean Energy Demonstrations

OCED was established to help scale the emerging technologies needed to tackle our nation's most pressing climate challenges. OCED's mission is to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption, and the equitable transition to a decarbonized energy system. OCED manages a demonstration portfolio of projects of more than $25 billion that include clean hydrogen, carbon management, advanced nuclear reactors, long-duration energy storage, and other industrial decarbonization technologies.

As part of its portfolio, OCED manages the Regional Clean Hydrogen Hubs Program, which includes up to $7 billion to establish H2Hubs across the nation, as well as a demand-side support mechanism to help encourage early adoption of hydrogen from the H2Hubs, totaling $8 billion. Funded through the Bipartisan Infrastructure Law, the H2Hubs will accelerate the commercial-scale deployment of clean hydrogen, helping to generate clean, dispatchable power; create a new form of energy storage; and decarbonize heavy industry and transportation. Together, the H2Hubs will kick-start a national network of clean hydrogen producers, consumers, and connective infrastructure while supporting the production, storage, delivery, and end use of clean hydrogen. The H2Hubs will also help to enable the development of diverse, domestic clean energy pathways across multiple sectors of the economy and serve as a central driver in helping communities benefit from clean energy investments, good-paying jobs, and improved energy security.

Advanced Research Projects Agency–Energy

ARPA-E catalyzes transformational energy technologies to enhance the economic and energy security of the United States. ARPA-E funds high-potential, high-impact projects that are too early for private sector investment but could disruptively advance the ways energy is generated, stored, distributed, and used. Some programs at ARPA-E have sought to develop technologies involving renewable energy and natural gas, with applications in the transportation, commercial, and industrial power sectors. In these areas, there are a number of efforts related to hydrogen. Focused R&D programs relevant to hydrogen or related technologies have included:

- Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH).
- Duration Addition to electricitY Storage (DAYS).
- Methane Pyrolysis Cohort.
- Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation (INTEGRATE).
- Integration and Optimization of Novel Ion-Conducting Solids (IONICS).
- Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL).
- Reliable Electricity Based on ELectrochemical Systems (REBELS).

Current and upcoming activities specifically related to clean hydrogen and fuel cell technologies include:

- Pioneering Railroad, Oceanic and Plane ELectrification with 1K energy storage systems (PROPEL-1K).
- H2SENSE to support the development of innovative approaches for hydrogen gas detection and quantification.
- Project portfolio to explore potential of geologic hydrogen.

[92] Loan Programs Office. 2024. "LPO Announces Conditional Commitment to Plug Power to Produce and Liquify Clean Hydrogen Fuel." May 14, 2024. www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-plug-power-produce-and-liquify-clean-hydrogen.

[93] Loan Programs Office. 2023. "Revisiting Prior Conditional Commitments: Monolith™ Inc." Jan. 19, 2023. www.energy.gov/lpo/articles/revisiting-prior-conditional-commitments-monolithtm-inc.

As shown in Figure 20 and Figure 21, there is specific interoffice collaboration on a number of technical areas, showing clearly delineated focus areas and areas leveraging coordination.

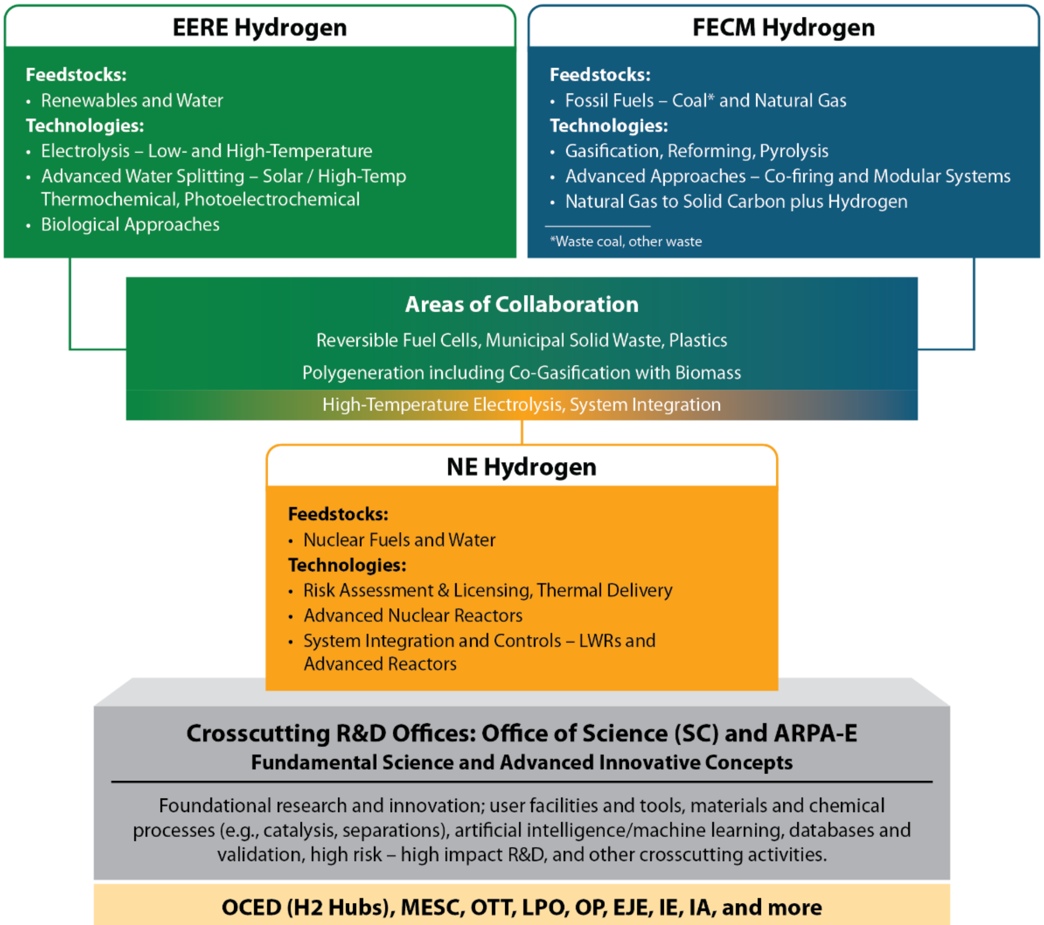


Figure 20. Collaboration on hydrogen production—key focus areas and technologies

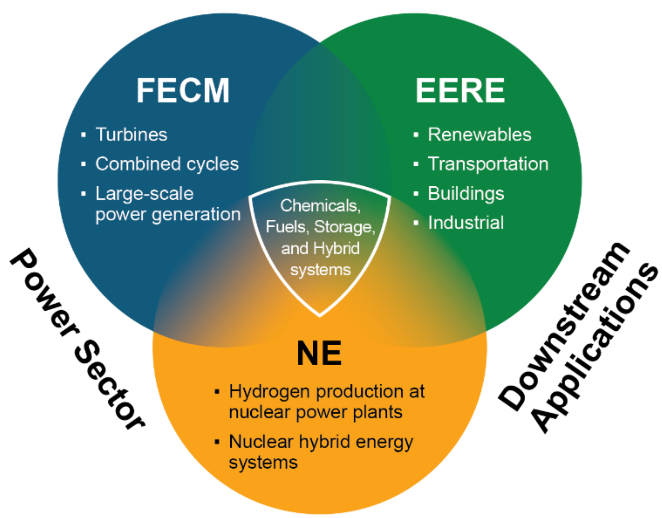


Figure 21. Collaboration on hydrogen applications—key focus areas

FECM and NE are primarily focused on large-scale power generation using fossil fuels or nuclear resources, while EERE focuses on renewables and end uses for hydrogen and fuel cells in multiple applications in the transportation sector, for stationary distributed power in buildings, and in industrial applications (through efforts in HFTO as well as the Industrial Efficiency and Decarbonization Office). Chemical and fuel production using hydrogen is an area of coordination between EERE and FECM, with FECM focusing on large-scale co-gasification and polygeneration and EERE focusing on smaller-scale production such as synfuels for the transportation sector or trigeneration for hydrogen fueling stations.

Federal and State Coordination

The Hydrogen Program actively pursues opportunities for coordination and collaboration with other Federal agencies. By exchanging information on RDD&D projects and collaborating on deployment activities, agencies can leverage each other's resources to achieve the maximum benefit from their efforts. For example, the Program collaborates extensively with the Department of Defense on early market deployment activities. The Department of Defense and DOE have held joint workshops to identify opportunities, challenges, and other areas of common interest.

DOE leads the Hydrogen Interagency Task Force (HIT),[94] which provides a forum for sharing research results, technical expertise, and lessons learned about hydrogen program implementation and technology deployment, as well as coordinating related projects. The HIT was launched to help execute the *U.S. National Clean Hydrogen Strategy and Roadmap*, which was required by Congress in the Bipartisan Infrastructure Law. This interagency group builds upon the "Hydrogen and Fuel Cell Interagency Task Force" authorized in the Energy Policy Act of 2005, which requires the Secretary of Energy to coordinate across agencies on hydrogen. Several collaboration opportunities exist across agencies, building on activities underway over more than a decade to accelerate progress. Details and updates will be available at https://www.hydrogen.gov/.

The Hydrogen Program coordinates closely with several state governments to help ensure that activities are well integrated at the Federal, state, and local levels. Coordinating with state-level activities is also essential for implementing the Program's overall strategy for real-world demonstrations, public outreach and education, and early market deployments.

Private Sector and Other Nongovernmental Partnerships

Stakeholder input is vital to Program planning, as well as to sustaining the Program's effectiveness and the value of its efforts. The Program's engagement with private sector and nonprofit stakeholders through key partnerships helps to ensure that the RDD&D efforts of government, academia, and industry are well coordinated, their diverse capabilities are well integrated, and their resources are effectively utilized.

One of these partnerships, U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), focuses on precompetitive, high-risk research needed to improve the energy efficiency of the nation's personal transportation system. A major goal of the partnership is to identify and develop the technologies required for the high-volume production of affordable light-duty vehicles, including electric, hybrid electric, advanced combustion, and hydrogen vehicles—along with the national infrastructure necessary to support them. In 2019, the Program expanded transportation-related collaboration to the 21st Century Truck Partnership with the Vehicle Technologies Office, specifically focused on advancing next-generation medium- and heavy-duty trucks, including the use of hydrogen fuel cells.[95] The Program also benefits from continual interaction with stakeholders through its involvement with a number of other organizations, including the Fuel Cell and Hydrogen Energy Association, which represents a broad range of stakeholders including manufacturers

[94] HFTO has led this group for well over a decade, consistent with Section 806 of the Energy Policy Act of 2005, 2 U.S.C. §16155, which directs DOE to lead a Hydrogen and Fuel Cell Interagency Task Force.

[95] Vehicle Technologies Office. 2024. "21st Century Truck Partnership." Accessed Oct. 3, 2024. www.energy.gov/eere/vehicles/21st-century-truck-partnership.

of fuel cell components, systems, and materials; hydrogen producers and fuel distributors; universities; government laboratories; and others.

Several other private-sector-based associations and coalitions coordinate with the program, including the Hydrogen Fuel Cell Partnership, California Hydrogen Business Council, California Stationary Fuel Cell Collaborative, Green Hydrogen Coalition, Colorado Hydrogen Network, New Jersey Hydrogen Coalition, Massachusetts Hydrogen Coalition, Ohio Fuel Cell Coalition, Renewable Hydrogen Coalition, and the growing number of state-related organizations involved in hydrogen.

International Coordination and Collaboration

The Program engages in multiple international activities and partnerships to share technology lessons learned, foster collaboration, and advance mutual RDD&D areas of interest at a global scale. Key examples include the Clean Energy and Hydrogen Energy Ministerials, International Energy Agency, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Mission Innovation, Partnership for Transatlantic Energy Cooperation, and various bilateral arrangements with countries involved in hydrogen and fuel cell activities.

Key examples spanning two decades of coordination and collaboration include:

- **International Energy Agency Technology Collaboration Programmes.** The Hydrogen Program has been active in the International Energy Agency Technology Collaboration Programme and served as vice chair of the Advanced Fuel Cells Technology Collaboration Programme and Hydrogen Technology Collaboration Programme. Created in 1990, the Advanced Fuel Cells Technology Collaboration Programme focuses on multiple fuel cell technologies across applications and currently has 18 member countries: Austria, Brazil, Canada, China, Croatia, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, South Africa, Spain, Sweden, Switzerland, and the United States.[96] The Hydrogen Technology Collaboration Programme was established in 1977 as a hub for international collaboration on hydrogen RD&D and analysis, and currently includes 24 member countries, the European Commission, and the United Nations Industrial Development Organization. The individual member countries include Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, Korea, Lithuania, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States.[97]
- **International Partnership for Hydrogen and Fuel Cells in the Economy.** Established in 2003, IPHE is an international intergovernmental partnership currently consisting of 20 member countries and the European Commission. Its objective is to accelerate progress in hydrogen and fuel cell technologies, and it provides a forum for sharing information on member country initiatives, policies, and technology status, as well as safety, regulations, codes, standards, and outreach. IPHE includes working groups on both Regulations, Codes, Standards, and Safety and Education and Outreach, as well as task forces such as the Hydrogen Production and Analysis task force to enable international trade of hydrogen. The Hydrogen Program, through representation from HFTO, served as the elected chair (from mid-2018 through the end of 2020) of IPHE. IPHE serves as one of the primary international mechanisms through which the Program coordinates and collaborates with other new and emerging partnerships such as the ministerials.
- **Generation IV International Forum.** Established in 2001, the Generation IV International Forum (GIF) was created as a cooperative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030. The VHTR (Very High Temperature Reactor) hydrogen production program aims at developing and optimizing high temperature thermochemical and electrolysis water splitting

[96] International Energy Agency. 2024. "Advanced Fuel Cells Technology Collaboration Programme: About us." Accessed Oct. 3, 2024. www.ieafuelcell.com/index.php?id=8.
[97] International Energy Agency. 2024. "Hydrogen." Accessed Oct. 3, 2024. www.iea.org/energy-system/low-emission-fuels/hydrogen.

processes, as well as defining and validating technologies for coupling any Gen IV Nuclear Reactor system to such process plants safely and securely through an international collaborative program.

- **International Atomic Energy Agency.** Engagement with IAEA led to U.S. Chairmanship of a technical committee that developed a seminal publication available as a Nuclear Energy Series document issued by IAEA on opportunities directly related to utilization of the light water reactor (LWR) fleet for diverse applications. Additionally, the NE office supports technical meetings on Advances in High Temperature Processes for Hydrogen production with nuclear energy in September 2023.

By incorporating input from international and domestic stakeholders, as well as through the in-depth expertise within the Hydrogen Program, strategies are developed to address the challenges in each of the key areas of hydrogen production, delivery, storage, and utilization as discussed in earlier sections. For example, DOE efforts support the recommendations outlined in the International Energy Agency's *The Future of Hydrogen* report released at the 2019 G20 Summit:[98]

1. "Establish a role for hydrogen in long-term energy strategies." Key sectors include refining, chemicals, iron and steel, freight and long-distance transport, buildings, and power generation and storage.
2. "Stimulate commercial demand for clean hydrogen." This includes scaling up both "blue" hydrogen (from fossil fuels with CCUS) and "green" hydrogen (using renewables), as well as water electrolysis using nuclear resources.
3. "Address investment risks of first-movers." New applications for hydrogen, as well as clean hydrogen supply and infrastructure projects, can be supported through tools such as loan guarantees to reduce risk.
4. "Support R&D to bring down costs." Alongside cost reductions from economies of scale, R&D is crucial to lower costs and improve performance.
5. "Eliminate unnecessary regulatory barriers and harmonize standards." Project developers face hurdles where regulations and permit requirements are unclear. Addressing safety, codes, and standards is necessary for a harmonized global supply chain.
6. "Engage internationally and track progress." Enhanced international cooperation is essential and supported by a number of partnerships.
7. "Focus on four key opportunities to further increase momentum over the next decade." These include enabling industrial ports as hubs for hydrogen at scale; using existing gas infrastructure to spur new clean hydrogen supplies; supporting transportation fleets, freight, and corridors; and enabling hydrogen shipping to jump-start international hydrogen trade.

DOE activities as outlined in this document are also aligned with the Global Action Agenda as developed through the Hydrogen Energy Ministerial in September 2019.[99] Key pillars include:

1. Collaboration on technologies and coordination on the harmonization of regulation, codes, and standards.
2. Promotion of information sharing and international joint R&D emphasizing hydrogen safety and infrastructure supply chains.
3. Study and evaluation of hydrogen's potential across sectors, including its potential for reducing both carbon dioxide emissions and other pollutants.
4. Communication, education, and outreach.[100]

Figure 22 summarizes the high-level strategies and enabling activities by DOE's programs in conjunction with key roles and responsibilities entailing increased private sector engagement. These activities also reflect input from the international recommendations cited above, as well as the *Road Map to a US Hydrogen Economy*, a document

[98] International Energy Agency. 2019. *The Future of Hydrogen*.
[99] International Energy Agency. 2024. "CEM Hydrogen Initiative." Accessed Oct. 9, 2024. https://www.iea.org/programmes/cem-hydrogen-initiative.
[100] Global Action Agenda. 2019. "Chair's Summary."

published in 2020 with analysis developed by roughly 20 leading industry stakeholders committed to developing a hydrogen economy in the United States.[101]

Hydrogen Strategy Emphasizes Collaborative Activities Between Government and Private Sector

	Enabling Activities by Government	Increasing Private Sector Role
	Foster RDD&D to reduce regulatory barriers and enable market penetration by private sector. Enable technology-neutral, all-of-the-above strategy.	Scale up market deployment across applications and sectors to enable economically viable technologies and achieve sustainable market penetration to realize energy, environmental, and economic security.
Hydrogen Production	RDD&D for H_2 production from diverse domestic resources to meet application-specific cost and performance metrics: $1/kg.	Scale up H_2 production, including CCUS and co-locate production with end use for focused, cohesive deployment efforts to demonstrate value proposition.
Hydrogen Delivery	RDD&D to enable low-cost, safe, reliable H_2 delivery/distribution and dispensing, including H_2 blends. Includes gaseous, liquid, and chemical carriers to meet cost targets of $2/kg to $5/kg.	Establish gaseous and liquid distribution, including liquefaction and fueling infrastructure to meet demand. Build out H_2 pipelines in key regions suitable for H_2 blends. Address barriers to H_2 delivery for export.
Hydrogen Storage	RDD&D of low cost, high capacity, safe H_2 storage for both on-board and stationary storage at varying scales, including high-pressure tanks, materials, chemical carriers, and liquid.	Develop supply chain including carbon fiber and other components. Support storage deployments across applications – for fueling stations, large scale (e.g., geologic) energy storage, tankers for H_2 export, and enabling terminal infrastructure.
Conversion: Fuel Cells and Combustion	RDD&D of diverse fuel cell and combustion technologies to enable high-efficiency, low-cost, and reliable components and systems across scales and applications.	Develop supply chain and domestic manufacturing capacity for fuel cells, turbines, and other components. Support deployments across applications and sectors at scale.
End-Use Applications	RDD&D to enable multiple applications across sectors (transportation, stationary, industrial). Initiate, assess, and optimize hybrid and integrated energy systems.	Scale up deployments in diverse applications to create critical mass for infrastructure. Demonstrate energy, emissions, and economic benefits for tangible business cases.
Cross-Cutting & Enabling Activities	Address safety, codes and standards (barriers), and develop best practices. Establish training and workforce development programs. Accelerate technology transition to the private sector.	Establish and update codes and standards to ensure consistency and harmonization and develop global market. Ensure safety best practices and workforce development to ensure competitive American workforce.

Figure 22. DOE Hydrogen Program strategies and enabling activities

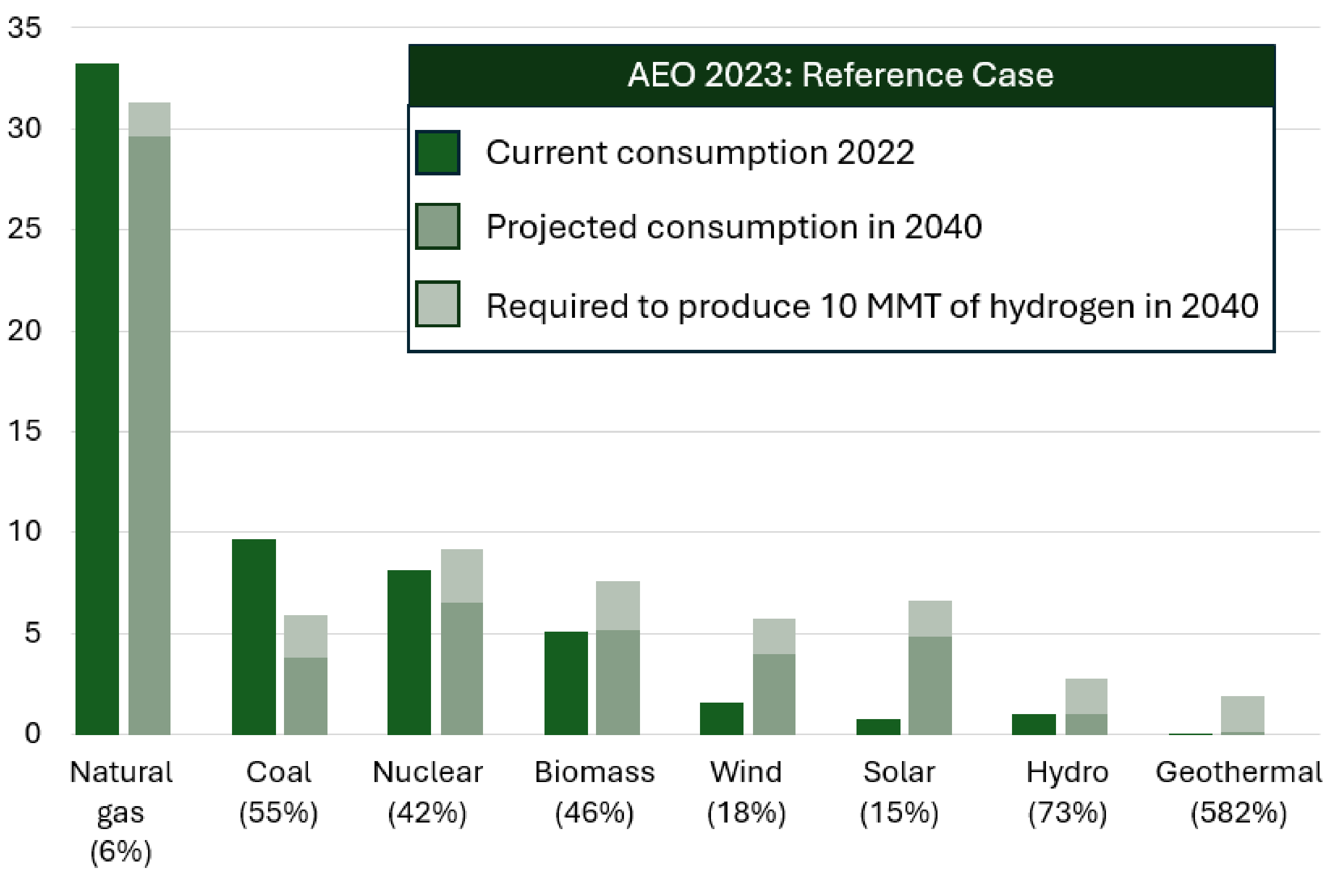
In summary, through the cohesive and coordinated efforts by DOE's various offices involved in hydrogen and related technology activities, and through extensive stakeholder input and collaboration, implementation of this plan will contribute to achieving the Hydrogen Program's vision: a prosperous future for the nation, in which clean hydrogen energy technologies are affordable, widely available, reliable, and an integral part of multiple sectors of the economy across the country.

[101] Fuel Cell and Hydrogen Energy Association. 2020. *Road Map to a US Hydrogen Economy*. www.ushydrogenstudy.org/.

Appendix A: Domestic Energy Resources Required To Produce 10 MMT of Hydrogen

A key aspect of DOE's hydrogen strategy is to enable hydrogen production from a diverse array of low-carbon domestic energy resources, including renewable resources (such as biomass, wind, and solar energy), nuclear energy, and fossil fuels (with CCUS). Figure A-1 offers insights into the ability of these domestic resources to meet the potential demand for hydrogen. Rather than select a specific market penetration assumption to determine the demand for hydrogen, the quantity of 10 MMT was selected as an example, as it represents current annual domestic hydrogen production. The figure shows the amount of each energy resource (e.g., natural gas, coal, wind, solar) that would be required if all 10 MMT of today's hydrogen production volume were to be produced by that single resource alone. That amount is then compared with both the current use of that resource and its projected use in 2040.

In the future, growth in hydrogen production is likely to be met through a combination of these resources, rather than any single resource alone. It is also important to note that what is shown here does not represent all the potential production pathways—there are a number of other promising pathways under development, including geologic hydrogen, pyrolysis, direct conversion of solar energy through photoelectrochemical means, waste to hydrogen, biological approaches, and high-temperature thermochemical systems. The results shown in Figure A-1 reflect updates made to analysis published by the National Renewable Energy Laboratory in 2020 with input from multiple DOE offices, as well as external stakeholders.[102]



[102] Connelly et al. 2020. Resource Assessment for Hydrogen Production.

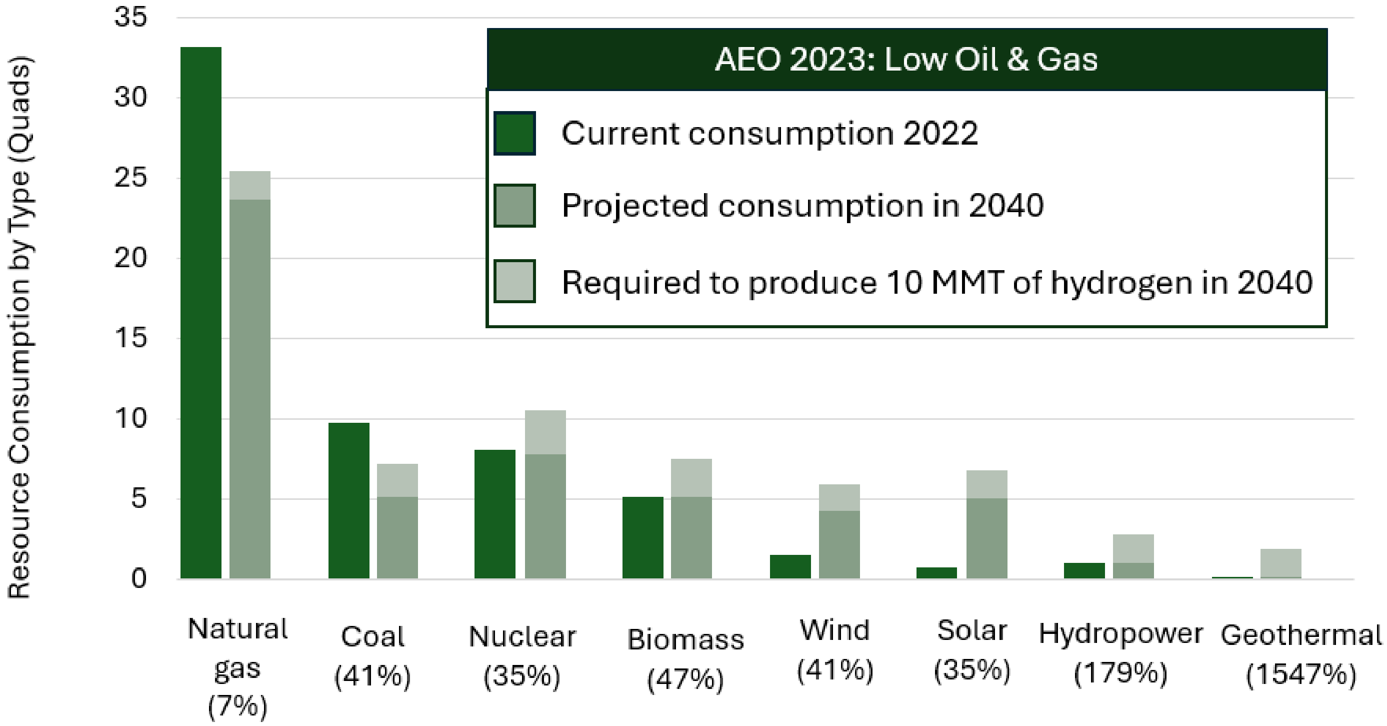


Figure A-1. The amount of each energy resource that would be required to produce 10 MMT/yr of hydrogen (using each resource on its own), relative to current (2022) and projected (2040) energy consumption in the Annual Energy Outlook's reference case (top) and low oil and gas case (bottom).

The dark green bars indicate current (2022) consumption of each resource, the next lighter shade represent projected (2040) consumption, and the lightest shaded bars depict the amount of additional resource that would be necessary to produce 10 MMT/yr of H_2 in 2040. The percentages in parentheses under the x-axis labels denote the increase in 2040 projected resource consumption needed to meet the 10-MMT hydrogen demand. This graph is an update **to previous analysis published** by the National Renewable Energy Laboratory in 2020. Key updates include (1) use of the 2023 Annual Energy Outlook to characterize current and 2040 consumption, rather than the 2019 edition,[103] and (2) use of energy equivalency values to characterize renewables rather than fossil fuel equivalency values.[104] The amount of resource required to produce 10 MMT of H_2 was estimated assuming hydrogen production technologies described in the 2020 resource report.[105]

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[103] Resource consumption of natural gas, coal, and biomass is depicted in units of higher heating value and sourced from Tables 2 and 17 from the 2023 Annual Energy Outlook. Resource consumption of nuclear power is sourced from Table 2 of the 2023 Annual Energy Outlook and reflects estimates from the U.S. Energy Information Administration of thermal energy generated by uranium when it is used in light-water nuclear reactors. Resource consumption of wind, solar, hydropower, and geothermal power is based off Table 17 of the 2023 Annual Energy Outlook.

[104] The Annual Energy Outlook estimates of resource consumption of renewables in 2022 and 2040 were modified to reflect an energy-equivalency-based conversion factor (3,412 Btu/kWh) rather than the fossil fuel equivalency conversion used in the report. This modification was made in alignment with the U.S. Energy Information Administration's shift in September 2023 to use energy equivalency conversions (3,412 Btu/kWh) to depict energy consumption from renewables, which is more consistent with international reporting: U.S. Energy Information Administration. 2023. "Changes to the Monthly Energy Review (MER)." www.eia.gov/totalenergy/data/monthly/change/.

[105] Estimates of renewable consumption required to produce 10 MMT of H_2 per year were modified from the 2020 analysis published by the National Renewable Energy Laboratory to reflect an energy-equivalency-based conversion factor, rather than the conversion based on fossil fuel equivalency used in the published report.

Appendix B: Glossary of Acronyms

AE	Arctic Energy Office
ARPA-E	Advanced Research Projects Agency–Energy
CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EJE	Office of Energy Justice and Equity
FECM	Office of Fossil Energy and Carbon Management
H_2	hydrogen
H2Hubs	Regional Clean Hydrogen Hubs Program
HFTO	Hydrogen and Fuel Cell Technologies Office
HIT	Hydrogen Interagency Task Force
IA	Office of International Affairs
IE	Office of Indian Energy Policy and Programs
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LPO	Loan Programs Office
MESC	Office of Manufacturing and Energy Supply Chains
MMT	million metric tons
NE	Office of Nuclear Energy
NH_3	ammonia
NO_x	nitrogen oxides
OCED	Office of Clean Energy Demonstrations
OE	Office of Electricity
OP	Office of Policy
OTT	Office of Technology Transitions
PEMFC	polymer electrolyte membrane fuel cell
R&D	research and development
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
SC	Office of Science
SMR	steam methane reforming
SOFC	solid oxide fuel cell

Appendix C: Contacts and Links

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Links to Relevant Organizations

DOE Hydrogen Program: www.hydrogen.energy.gov

DOE Office of Energy Efficiency and Renewable Energy: www.energy.gov/eere/office-energy-efficiency-renewable-energy

- Hydrogen and Fuel Cell Technologies Office: www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office

DOE Office of Fossil Energy and Carbon Management: www.energy.gov/fecm/office-fossil-energy-and-carbon-management

- Office of Carbon Management: www.energy.gov/fecm/office-carbon-management
- Hydrogen with Carbon Management: www.energy.gov/fecm/hydrogen-carbon-management
- Office of Resource Sustainability: www.energy.gov/fecm/office-resource-sustainability

DOE Office of Nuclear Energy: www.energy.gov/ne/office-nuclear-energy

DOE Office of Electricity: www.energy.gov/oe/office-electricity

DOE Office of Science: www.energy.gov/science/office-science

- Basic Energy Sciences: www.energy.gov/science/bes/basic-energy-sciences
- Energy Frontier Research Centers: science.osti.gov/bes/efrc
- Energy Innovation Hubs: science.osti.gov/bes/Research/DOE-Energy-Innovation-Hubs

- SC Energy Earthshots: https://science.osti.gov/Initiatives/SCEarthshots

DOE Loan Programs Office: www.energy.gov/lpo/loan-programs-office

DOE Office of Manufacturing and Energy Supply Chains: www.energy.gov/mesc/office-manufacturing-and-energy-supply-chains

DOE Office of Clean Energy Demonstrations: www.energy.gov/oced/office-clean-energy-demonstrations

- Regional Clean Hydrogen Hubs: www.energy.gov/oced/regional-clean-hydrogen-hubs-0

Advanced Research Projects Agency–Energy: arpa-e.energy.gov/

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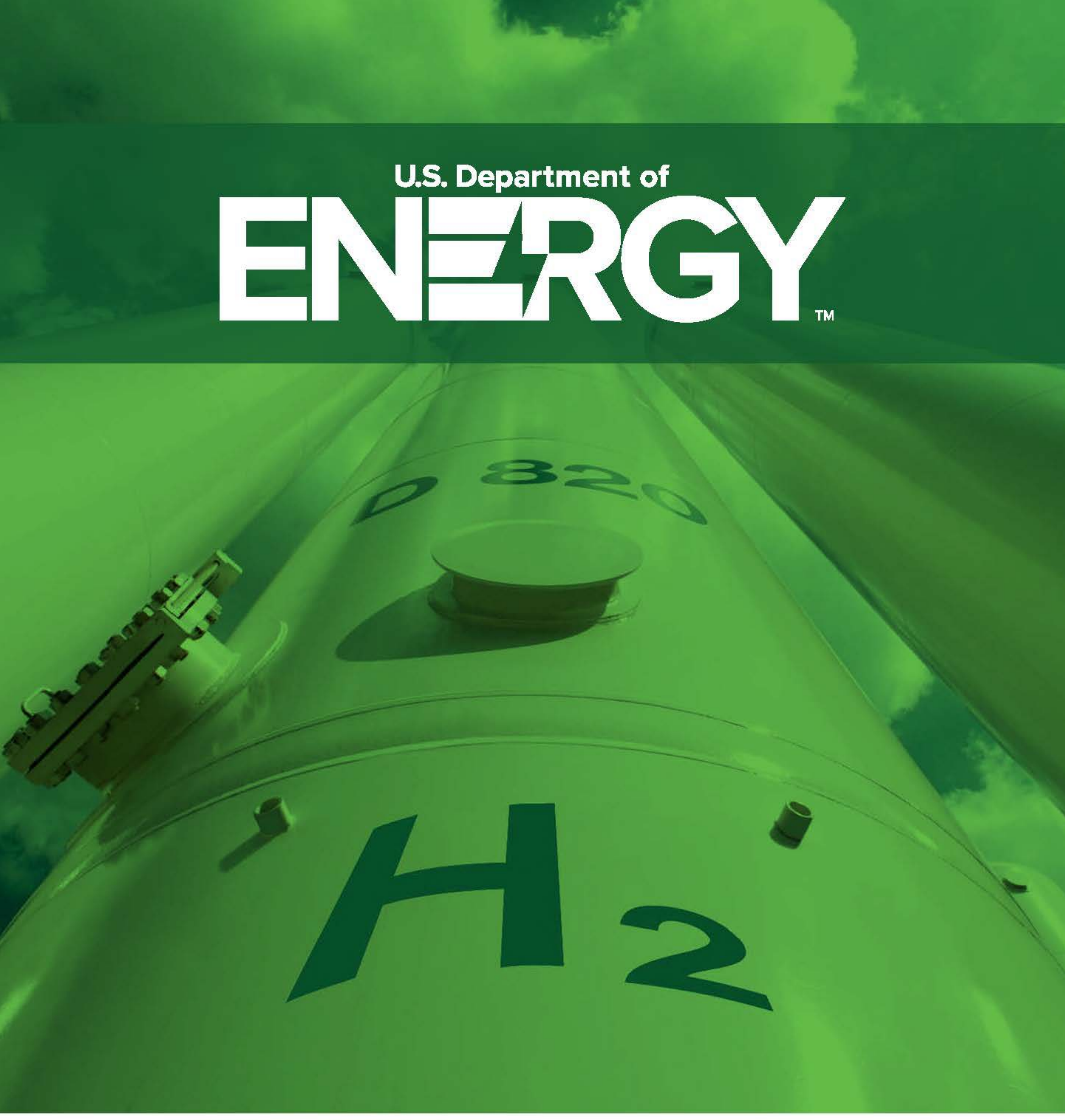

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