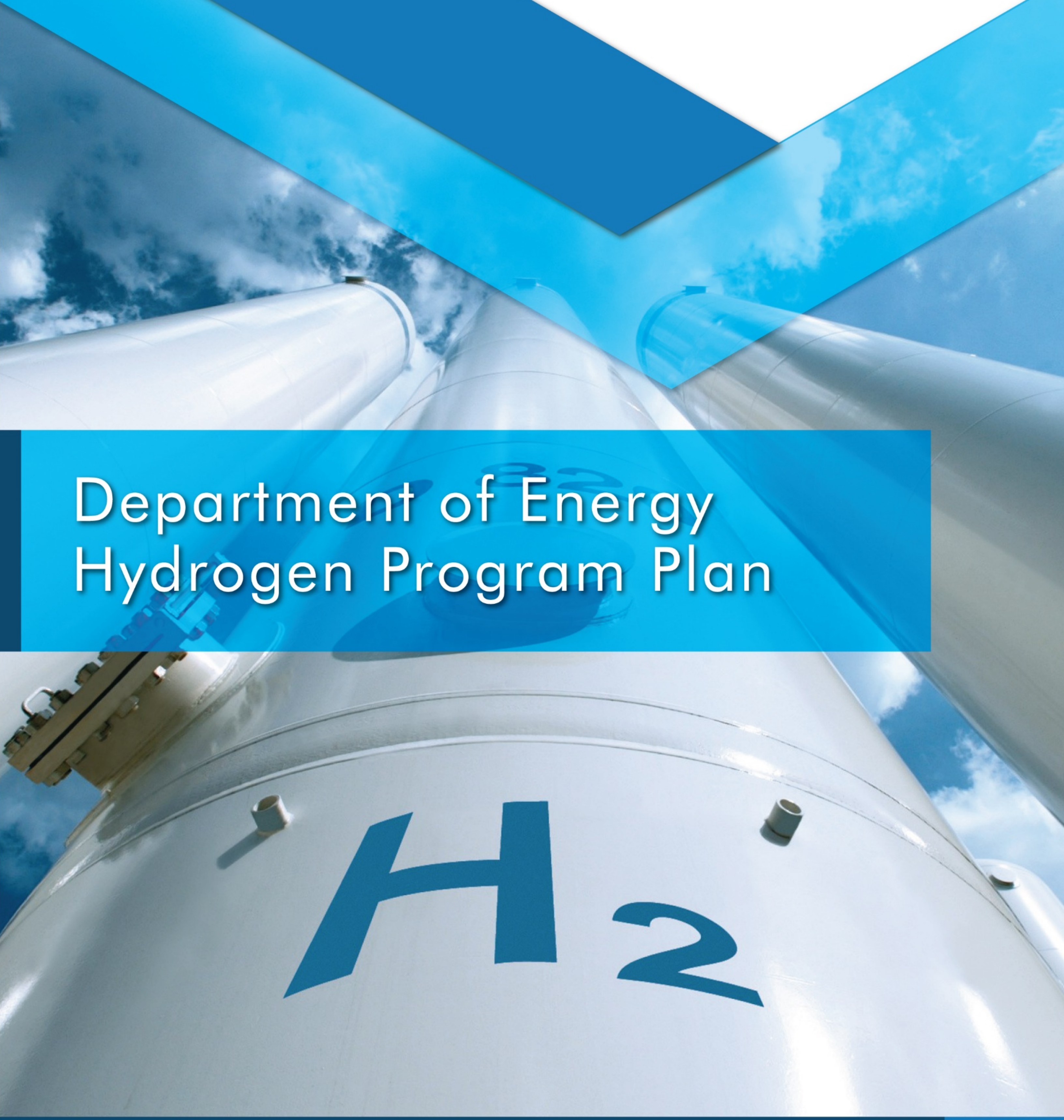
U.S. DEPARTMENT OF
ENERGY

Department of Energy Hydrogen Program Plan



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To Our Stakeholders

The U.S. economy is becoming more agile and innovative in response to continuing economic and environmental challenges and to the regional demands for clean electricity, fuels, and other products. At the same time, the past decade has demonstrated the need for an all-of-the-above strategy to support the U.S. economy and energy security, and to protect the environment.

Hydrogen is a versatile fuel that offers a path to sustainable long-term economic growth. It can add value to multiple sectors in the economy and support America's ongoing manufacturing renaissance. It can serve as a sustainable fuel for transportation and as input to produce electricity and heat for homes. And, carbon-free hydrogen could even be exported to markets that are looking for carbon-free energy.

But realizing the true potential for hydrogen requires a commitment to continued research and development as well as ramping up demonstrations and deployments with the private sector to achieve scale. Unlike other fuels, hydrogen requires more integration of the fossil, nuclear, and renewable energy systems, and it will take an integrated approach from all energy sectors to realize the full potential and benefits of hydrogen.

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 the research, development, and demonstration efforts of the Offices of Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, Electricity, Science, and ARPA-E to advance the production, transport, storage, and use of hydrogen across different sectors of the 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.

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Preface – About this Document

The *Department of Energy (DOE) Hydrogen Program Plan* (the *Program Plan or Plan*) outlines the strategic high-level focus areas of 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, and demonstration (RD&D) activities on hydrogen technologies. 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 version of the *Plan* updates and expands upon previous versions including the *Hydrogen Posture Plan*[1] and the *DOE Hydrogen and Fuel Cells Program Plan,*[2] 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 (EPACT 2005)[3](see box) that the Energy Secretary transmit to Congress a coordinated plan for DOE's hydrogen and fuel cell activities. For historical context, the original *Posture Plan*, issued in 2004, outlined a coordinated plan for DOE and the U.S. Department of Transportation to meet the goals of the Hydrogen Fuel Initiative (HFI) and implement the *2002 National Hydrogen Energy Technology Roadmap*.[4] The HFI was launched in 2004 to accelerate research, development, and demonstration (RD&D) of hydrogen and fuel cell technologies for use in transportation, electricity generation, and portable power applications. The *Roadmap* provided a blueprint for the public and private efforts required to fulfill a long-term national vision for hydrogen energy, as outlined in *A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*.[5] Both the *Roadmap* and the *Vision* were developed out of meetings involving DOE, industry, academia, non-profit organizations, and other stakeholders. The *Roadmap*, the *Vision*, the *Posture Plans*, the 2011 *Program Plan*, and the results of key stakeholder workshops continue to form the underlying basis for this current edition of the *Program Plan*.

This edition of the *Program Plan* reflects the Department's focus on conducting coordinated RD&D activities to enable the adoption of hydrogen technologies across multiple applications and sectors. It 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's *Hydrogen Strategy: Enabling a Low Carbon Economy*,[6] the Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office *Multi-year RD&D Plan*,[7] the Office of Nuclear Energy's *Integrated Energy Systems 2020 Roadmap,*[8] and the Office of Science's *Basic*

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[1] U.S. Department of Energy and U.S. Department of Transportation. December 2006. "Hydrogen Posture Plan. An Integrated Research, Development and Demonstration Plan." https://www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan_dec06.pdf

[2] U.S. Department of Energy. September 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." https://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf.

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

[4] U.S. Department of Energy. November 2002. "National Hydrogen Energy Roadmap: Production, Delivery, Storage, Conversion, Applications, Public Education and Outreach." https://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf.

[5] U.S. Department of Energy. February 2002. "A National Vision of America's Transition to a Hydrogen Economy – To 2030 and Beyond." https://www.hydrogen.energy.gov/pdfs/vision_doc.pdf.

[6] U.S. Department of Energy, Office of Fossil Energy. 2020. "Hydrogen Strategy: Enabling a Low-Carbon Economy." https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

[7] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office. "Multi-Year Research, Development and Demonstration Plan." Accessed online: https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22.

[8] U.S. Department of Energy, Office of Nuclear Energy. September 2020. Idaho National Laboratory: Shannon Bragg-Sitton, C. Rabiti, J. E. O'Brien, T. J. Morton, R. Boardman, S. Yoon, J.S. Yoo, K. L. Frick, M. S. Greenwood, and R. Vilim. "Integrated Energy Systems: 2020 Roadmap." https://www.osti.gov/biblio/1670434/.

Research Needs for the Hydrogen Economy.[9] Many of these documents are also in the process of updates and revisions and will be posted online.

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

Energy Policy Act of 2005 (EPACT), Title VIII – Hydrogen

Activities within the Plan address authorizations in the Energy Policy Act of 2005, including Title VIII, which include:

SEC. 802. PURPOSES.

The purposes of this title are– (1) to enable and promote comprehensive development, demonstration, and commercialization of hydrogen and fuel cell technology in partnership with industry; (2) to make critical public investments in building strong links to private industry, institutions of higher education, National Laboratories, and research institutions to expand innovation and industrial growth; (3) to build a mature hydrogen economy that creates fuel diversity in the massive transportation sector of the United States; (4) to sharply decrease the dependency of the United States on imported oil, eliminate most emissions from the transportation sector, and greatly enhance our energy security; and (5) to create, strengthen, and protect a sustainable national energy economy.

SEC. 804. PLAN.

Not later than 6 months after the date of enactment of this Act, the Secretary shall transmit to Congress a coordinated plan for the programs described in this title and any other programs of the Department that are directly related to fuel cells or hydrogen.

SEC. 805. PROGRAMS.

IN GENERAL.–The Secretary, in consultation with other Federal agencies and the private sector, shall conduct a research and development program on technologies relating to the production, purification, distribution, storage, and use of hydrogen energy, fuel cells, and related infrastructure.

GOAL.–The goal of the program shall be to demonstrate and commercialize the use of hydrogen for transportation (in light duty vehicles and heavy-duty vehicles), utility, industrial, commercial, and residential applications.

ACTIVITIES.–The Secretary, in partnership with the private sector, shall conduct programs to address– (1) production of hydrogen from diverse energy sources, including–

    (A) fossil fuels, which may include carbon capture and sequestration;
    (B) hydrogen-carrier fuels (including ethanol and methanol);
    (C) renewable energy resources, including biomass; and
    (D) nuclear energy;

(2) use of hydrogen for commercial, industrial, and residential electric power generation;

(3) safe delivery of hydrogen or hydrogen-carrier fuels, including–

    (A) transmission by pipeline and other distribution methods; and
    (B) convenient and economic refueling of vehicles either at central refueling stations or through distributed onsite generation;

(4) advanced vehicle technologies, including–

    (A) engine and emission control systems;
    (B) energy storage, electric propulsion, and hybrid systems;
    (C) automotive materials; and
    (D) other advanced vehicle technologies;

(5) storage of hydrogen or hydrogen-carrier fuels, including development of materials for safe and economic storage in gaseous, liquid, or solid form at refueling facilities and onboard vehicles;

(6) development of safe, durable, affordable, and efficient fuel cells, including fuel-flexible fuel cell power systems, improved manufacturing processes, high-temperature membranes, cost-effective fuel processing for natural gas, fuel cell stack and system reliability, low temperature operation, and cold start capability; and

(7) the ability of domestic automobile manufacturers to manufacture commercially available competitive hybrid vehicle technologies in the United States.

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[9] U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences. 2004. "Basic Research Needs for the Hydrogen Economy." https://www.hydrogen.energy.gov/pdfs/nhe_rpt.pdf.

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, and deployment (RD&D) of hydrogen and related technologies in the United States. The *Plan* provides an overview of core technology areas, challenges, and research and development (R&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 Energy Efficiency and Renewable Energy (EERE), Fossil Energy (FE), Nuclear Energy (NE), Electricity (OE), and Science (SC), and coordinates with the Advanced Research Program Agency – Energy (ARPA-E). While each office has its own planning documents, including program plans and multiyear RD&D plans, this overarching document provides a high-level framework summarizing activities relevant to all offices. This *Plan* updates the previous version, which built upon preceding strategic and planning documents including the *DOE Hydrogen Posture Plan*[10] and the *National Hydrogen Energy Roadmap*.[11] 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.[12]

This *Plan* builds upon aspects in the individual DOE office plans and documents, including FE's *Hydrogen Strategy: Enabling a Low-Carbon Economy*,[13] EERE's Hydrogen and Fuel Cell Technologies *Multi-Year RD&D Plan*,[14] NE's hydrogen related plans, and SC's *Basic Research Needs for the Hydrogen Economy*.[15] 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*.

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. Hydrogen can be derived from a variety of domestically available primary 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, 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 R&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

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[10] U.S. Department of Energy, December 2006, op cit.
[11] U.S. Department of Energy, February 2002, op cit.
[12] U.S. Department of Energy. 2020. DOE Hydrogen and Fuel Cells Program, "Program Areas." Accessed online: https://www.hydrogen.energy.gov/program_areas.html.
[13] U.S. Department of Energy, Office of Fossil Energy, 2020, op.cit.
[14] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office, op. cit.
[15] U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, 2004, op.cit.

in the mid-1970s when energy security and dependence on foreign oil were a major concern. Over the years, DOE established robust R&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[16] and the Energy Policy Act of 2005 (EPACT).[17]

Hydrogen Overview—Benefits and Uses

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, or 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.

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.

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 known fuels—3X 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 in a variety of domestic industries, such as the manufacturing of steel, cement, ammonia, and other chemicals.

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 potential for hydrogen and related technologies. And this potential is being recognized worldwide, with investments by government and industry ramping up in many countries. Industry has projected a potential $2.5 trillion global market for hydrogen technologies by 2050,[18] and annual shipments of fuel cells have increased 15-fold since 2015, now at over 1 gigawatt (1 GW).[19] For the first time, a coalition of major industries teamed together to develop an industry-led roadmap on the potential for hydrogen in the United States. The roadmap report concludes that by 2050, the U.S. hydrogen economy could lead to an estimated $750 billion per year in revenue and a cumulative 3.4 million jobs.[20] Industry is starting to invest in large-scale hydrogen projects in multiple regions. Examples include hydrogen production, storage, and end use in turbines through the $1 billion Advanced Clean Energy Storage project in Utah;

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[16] U.S. Congress. "Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990, P.L.101-566", November 1990. Accessed online: https://www.congress.gov/bill/101st-congress/senate-bill/639.

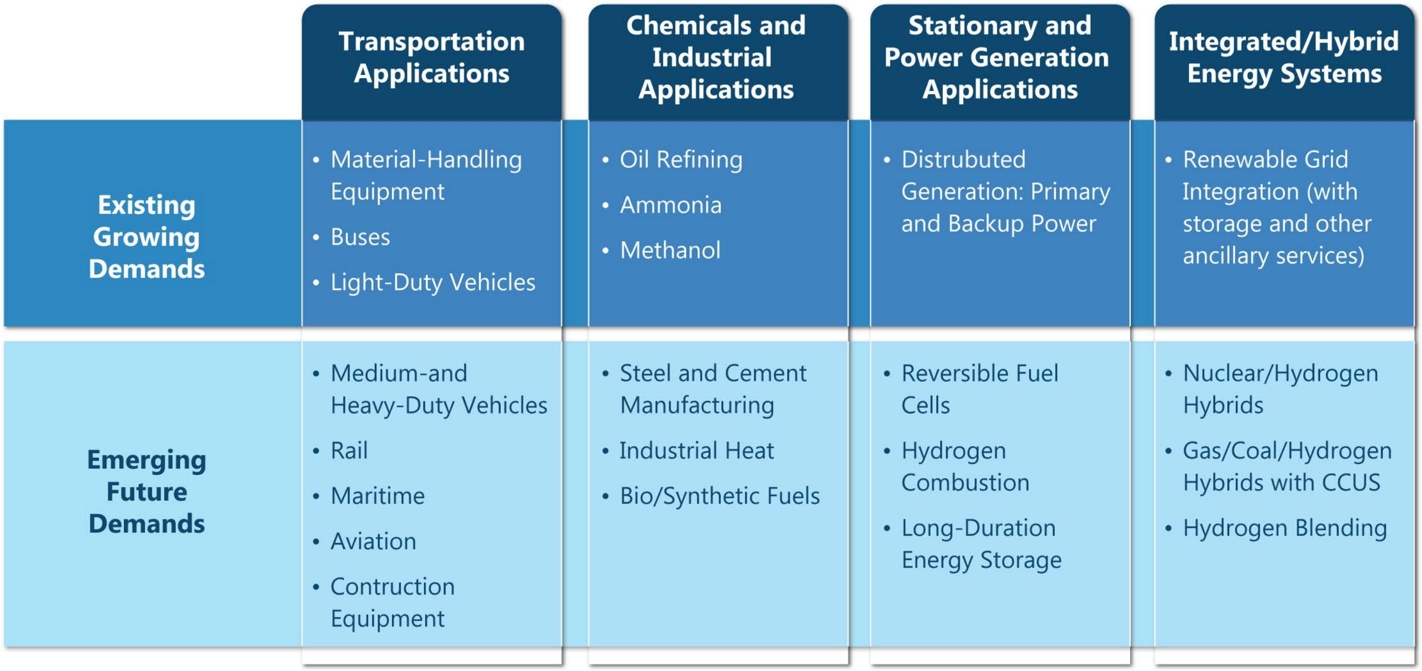
[17] U.S. Congress, August 2005, op cit.

[18] Hydrogen Council. November 2017. "Hydrogen Scaling Up. A Sustainable Pathway for the Global Energy Transition." https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf..

[19] E4 tech. December 2019. "The Fuel Cell Industry Review 2019."

[20] UShydrogenstudy.org. 2019. "Roadmap to a US Hydrogen Economy." www.ushydrogenstudy.org.

a 5 MW electrolyzer project planned in Washington State; first-of-a-kind nuclear-to-hydrogen projects in multiple states; and a 20 MW electrolyzer plant to produce hydrogen from solar power in Florida.



	Transportation Applications	Chemicals and Industrial Applications	Stationary and Power Generation Applications	Integrated/Hybrid Energy Systems
Existing Growing Demands	• Material-Handling Equipment • Buses • Light-Duty Vehicles	• Oil Refining • Ammonia • Methanol	• Distrubuted Generation: Primary and Backup Power	• Renewable Grid Integration (with storage and other ancillary services)
Emerging Future Demands	• Medium-and Heavy-Duty Vehicles • Rail • Maritime • Aviation • Contruction Equipment	• Steel and Cement Manufacturing • Industrial Heat • Bio/Synthetic Fuels	• Reversible Fuel Cells • Hydrogen Combustion • Long-Duration Energy Storage	• Nuclear/Hydrogen Hybrids • Gas/Coal/Hydrogen Hybrids with CCUS • Hydrogen Blending

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 45 over the past few years and over 145 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 of this transition has been enabled by R&D advances from DOE. Over the past 20 years, DOE has invested more than $4 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 carbon-free hydrogen for less than $2 per kg with carbon capture and storage. DOE funded R&D has also reduced the cost of transportation fuel cells by 60% and quadrupled durability, and has resulted in over 1,100 U.S. patents issued and over 30 commercial technologies in the market.[21]

The key technical challenges for hydrogen and related technologies are cost, durability, reliability, and performance, as well as the lack of hydrogen 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. Non-technical barriers also need to be addressed, such as developing and harmonizing codes and standards, fostering best practices for safety, and developing a robust supply chain and workforce.

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[21] (Patents and technologies resulting from RD&D funded by the EERE Hydrogen and Fuel Cell Technologies Office.) Steele, Lindsay. Pacific Northwest National Laboratory. September 2020. "2019 Patent Analysis for the U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office." PNNL-SA-156721. https://www.energy.gov/sites/prod/files/2020/10/f79/hfto-2019-patent-analysis.pdf.

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, 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, 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 • Advanced and innovative hydrogen production techniques from renewable, fossil, and nuclear energy resources, including hybrid and fuel-flexible approaches • Lower-cost and more-efficient technologies for producing hydrogen from water, fossil fuels, biomass, and waste • Low-cost and environmentally sound carbon capture, utilization, and storage technologies
DELIVERY: Hydrogen can be transported and dispensed as either 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 will 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: (i) physical storage, which includes high-pressure tanks and liquid hydrogen; or (ii) and material-based processes that incorporate hydrogen in chemical compounds, with the potential for higher capacities at ambient temperature and pressure. Additional approaches—such as geologic storage—may be needed for large-scale, long-term hydrogen storage.	• Lower-cost hydrogen storage systems • Higher storage capacity, with reduced weight and volume • Large-scale storage, including onsite bulk emergency supply and in geologic formations • Optimized storage strategies for co-locating stored hydrogen with end-use applications to meet throughput and dynamic response requirements and reduce investment cost
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 (heavy-duty transportation, stationary power, industrial and chemical applications, etc.) 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 grid-integration to validate hydrogen energy storage and grid services
MANUFACTURING AND SUPPLY CHAIN: Advanced manufacturing processes and a robust supply chain for hydrogen, fuel cell, and	• Standardized manufacturing processes, quality control, and optimized design-for-manufacturing

Key Aspects of the Hydrogen Energy System	Needs and Challenges
hydrogen turbine technologies can enable cost reductions and commercial-scale production.	• Additive and automated manufacturing processes • Design for recyclability and waste reduction
SAFETY, CODES AND STANDARDS: Technically sound codes and standards will 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 will 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 (such as in turbines) as well as for fuel cells (such as in high-throughput fueling for heavy-duty applications, including trucks, marine, and rail) • Improved safety information and sharing of best practices and lessons learned
EDUCATION AND WORKFORCE: A highly skilled workforce can effectively respond to growth in hydrogen-related industries, and can support and sustain a national competitive advantage in this advanced energy technology field. Broader understanding of hydrogen and related technologies can build confidence in the safe use of hydrogen as an energy carrier among key constituencies, including investors, policy-makers, and the general public.	• 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) • 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 timeframe 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.

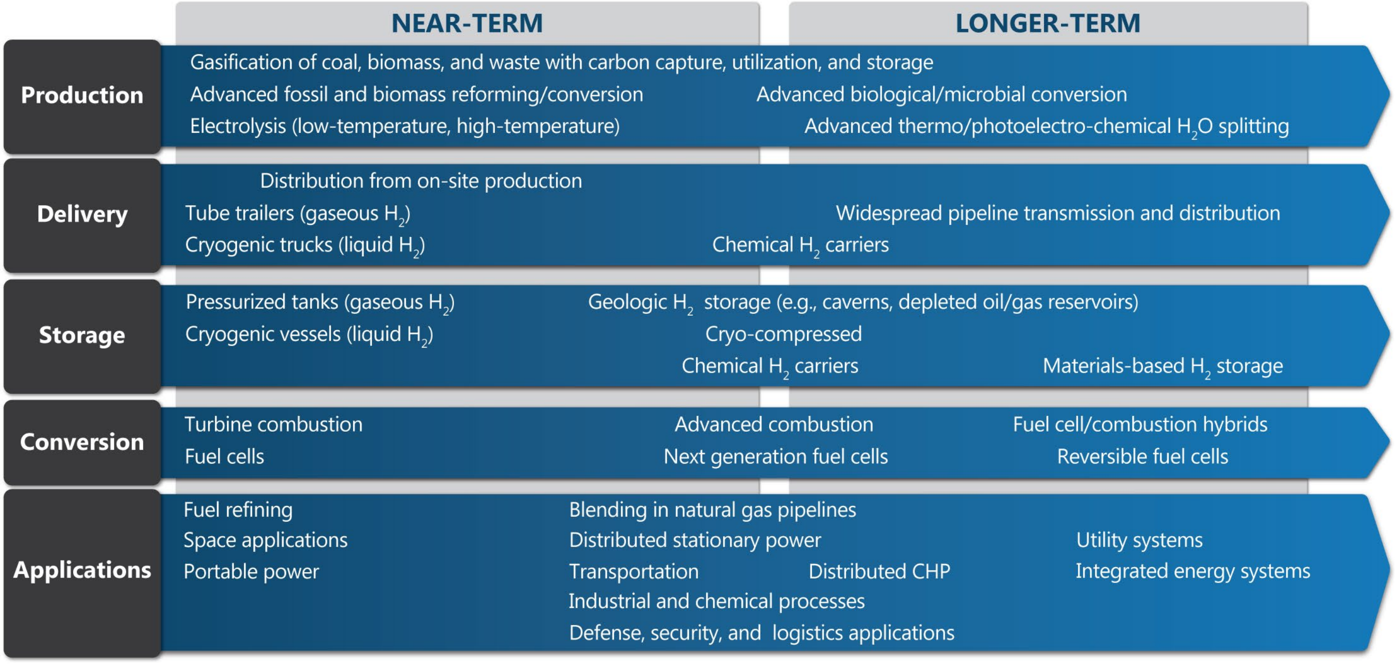

Figure 2. Key hydrogen technology options

2 DOE Hydrogen Program

Program Mission

The mission of the DOE Hydrogen Program is to research, develop, and validate transformational hydrogen and related technologies including fuel cells and turbines, and to address institutional and market barriers, to ultimately enable adoption across multiple applications and sectors. Development of hydrogen energy from diverse domestic resources will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the nation's prosperity throughout the 21st century and beyond.

Vision

The Program's vision is a prosperous future for the nation, in which clean hydrogen energy technologies are affordable, widely available and reliable, and are an integral part of multiple sectors of the economy across the country.

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

- Overcome technical barriers through basic and applied research and development
- 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, education and workforce development, 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, and energy security

In addition to participation from EERE, FE, NE, OE, and SC, the Program also coordinates with other relevant DOE efforts, including those in the Advanced Research Projects Agency-Energy (ARPA-E); the Office of Cybersecurity, Energy Security, and Emergency Response; and crosscutting DOE initiatives such as the Energy Storage Grand Challenge, Advanced Manufacturing, Grid Modernization, Integrated Energy Systems, Water Security Grand Challenge, and Artificial Intelligence. Each of these offices and initiatives manage hydrogen technology activities related to their missions. EERE, FE, and NE focus their RD&D activities on their respective energy sources, feedstocks, and target applications. All of these activities are coordinated to achieve a cohesive and strategically managed effort. More information on Program execution and collaboration is provided in Chapter 4.

Hydrogen at Scale—A Guiding Framework

H2@Scale[22] 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. 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.

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[22] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office. 2020. "H2@Scale," https://www.energy.gov/eere/fuelcells/h2-scale.

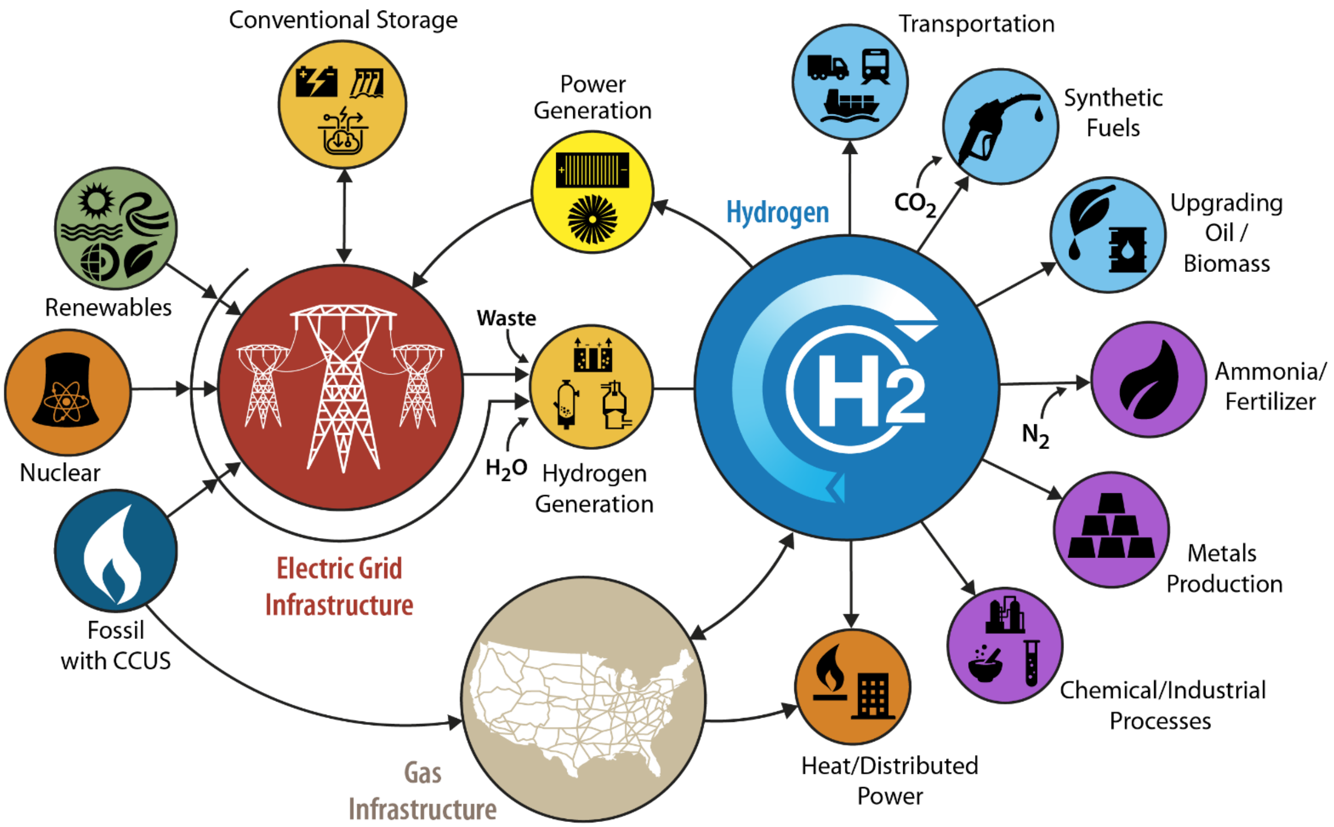

Figure 3. Conceptual H2@Scale energy system[23]

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 will 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 bio-fuels); 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 back-up 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 Chapter 3 of this *Plan*. 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.[24]

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

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[23] Source: U.S. Department of Energy, 2020, op. cit.: Schematic developed over three 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.'

[24] 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.

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 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, and tradeoffs between them. Results from these analyses are used to help guide R&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.

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. Table 2 shows today's hydrogen demand of 10 million metric tonnes (MMT)/year, and the economic potential for hydrogen in specific sectors at a total of 41 MMT/year assuming R&D success in key areas such as developing low cost electrolyzers.

> By 2050, the United States could see a two-to four-fold increase in hydrogen demand across the nation.

Table 2. Current consumption and future economic consumption potential of hydrogen in the United States (MMT/year)[25]

		Today	R&D Success Scenario
Demand Applications	**Oil refining**	6	7
	Metals refining	*negligible*	4
	Ammonia production	3	4
	Biofuels/synfuels production	1	9
	Transportation FCEVs (LDVs, MDVs, HDVs)[25]	*negligible*	17
Total hydrogen market		**10**	**41**

National labs have assessed various scenarios that show a range from 22 to 41 MMT/year as the economic potential for hydrogen demand—*two to four times the current demand.*[27] As new markets emerge (such as off-road transportation like marine applications or data centers), this economic potential may increase and will be assessed periodically through updated analyses.

In addition to DOE analysis, a group of over 20 industry partners projected a two-fold increase in hydrogen demand, to 20 MMT, by 2050 as a base case scenario, and a six-fold increase in an ambitious scenario.[28] Given uncertainties across sectors, markets, and technologies, these results are fairly consistent. Based on these two scenarios ("base" and "ambitious"), hydrogen could account for between 1% and 14% of total energy demand in the United States.

The Program has also determined the availability of domestic resources for hydrogen production across the country. Figures 4 through 14 depict the locations and quantities of fossil and renewable energy feedstocks throughout the United States, along with the locations of nuclear power plants and locations where hydrogen may be produced as a by-product in the near future. The nation's energy resources are geographically widespread, and fossil, nuclear, and renewable feedstocks are each independently sufficient to support at least a doubling of domestic hydrogen consumption.[29]

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[25] Ruth, Mark F., 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 Hydrogen Concept within the United States." National Renewable Energy Laboratory. NREL/TP-6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.

[26] The R&D Success scenario assumes fuel cell electric vehicle (FCEV) penetration of 18% to 26% in the light-, medium-, and heavy-duty vehicle sectors.

[27] Ruth, et.al, 2020, op. cit.

[28] UShydrogenstudy.org, 2019, op.cit.

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

Today, many states across the country have hydrogen production facilities, as shown in Figure 4. Most of these are steam methane reforming facilities, but a relatively small amount of hydrogen is also produced via water electrolysis or as a byproduct in chemical processing facilities such as chlor-alkali production and ethylene cracking.

The widespread availability of shale gas throughout the United States (as shown in Figure 5), along with additional natural gas reserves, offer more opportunities to produce hydrogen from natural gas in many regions. Coal is also widely available throughout the United States, as shown in Figure 6. Both natural gas and coal can be used with carbon capture to produce hydrogen today with no carbon dioxide emissions.

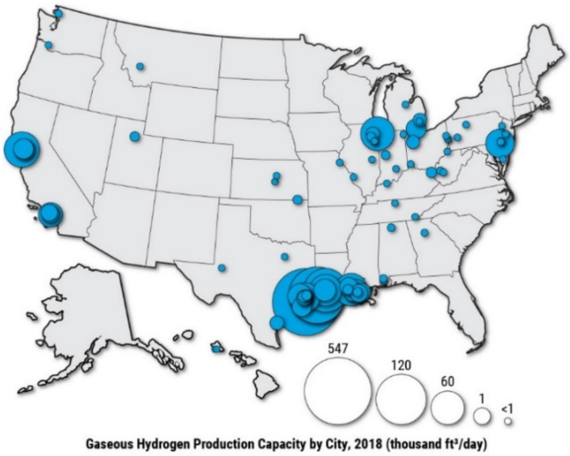
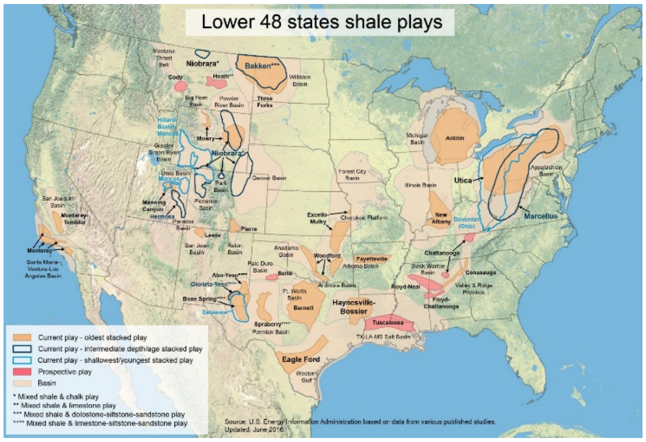


Figure 4. Gaseous hydrogen production units in the United States.[30]



Source: U.S. Energy Information Administration based on data from various published studies. Updated: June 2016

Figure 5: Shale gas plays within the United States[31]

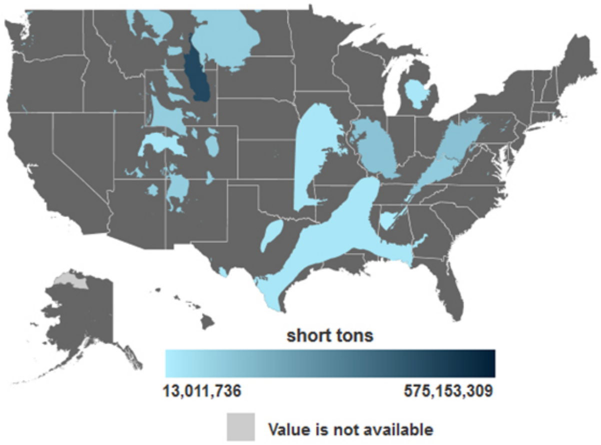


Figure 6: Domestic coal productive capacity[32]

Byproduct hydrogen from cracking natural gas liquids also offers opportunities for readily available, low-cost hydrogen, with locations shown in Figure 7. The production capacity of this by-product hydrogen is currently about 2 MMT/year, with roughly an additional 1.5 MMT/year expected from planned steam cracking plants in the next several years. If harnessed, this resource alone could provide 35% of today's hydrogen consumption and offers opportunities to harness regional availability and co-locate relevant end-use applications.

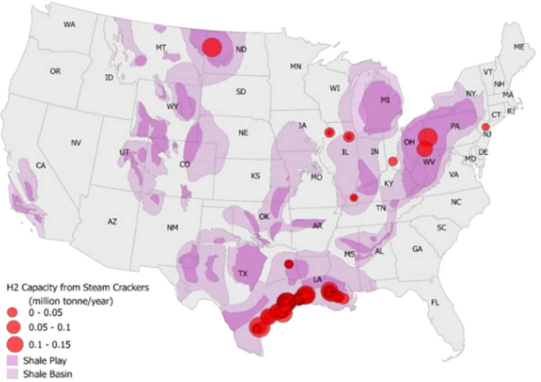


Figure 7. Hydrogen production capacity from current and planned steam crackers in the United States[33]

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[30] Map created by NREL (2020). Data source: IHS Markit, 2018 Chemical Economics Handbook: Hydrogen, London: IHS Markit 2020.

[31] U.S. Energy Information Administration based on data from various sources, June 2016, https://www.eia.gov/maps/maps.htm. Shale plays are shale formations containing significant accumulations of natural gas and which share similar geologic and geographic properties.

[32] U.S. Energy Information Administration. 2018. "Coal Data Browser – Productive Capacity 2018". Accessed online: https://www.eia.gov/coal/data/browser/#/topic/30?agg=0,1&mntp=g&geo=g0000000000003vu&linechart=COAL.PRODUCTIVE_CAP.TOT-US.A&columnchart=COAL.PRODUCTIVE_CAP.TOT-US.A&map=COAL.PRODUCTIVE_CAP.TOT-US.A&freq=A&start=2001&end=2018&ctype=map&ltype=pin&rtype=b&maptype=0&rse=0&pin=

[33] Lee, Dong-Yeon and A. Elgowainy. 2018. "By-product hydrogen from steam cracking of natural gas liquids (NGLs): Potential for large-scale hydrogen fuel production, life-cycle air emissions reduction, and economic benefit."

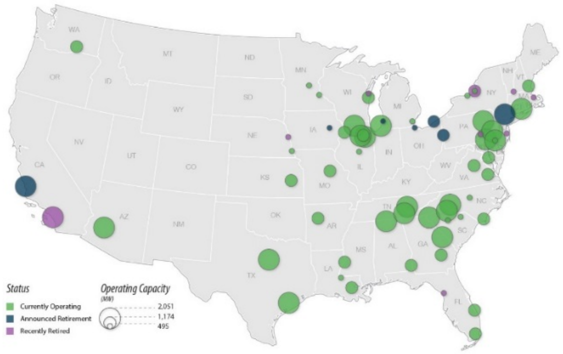

Figure 8. The locations of nuclear power plants in the United States[34]

In addition to well established processes like steam methane reforming, water-splitting processes—including electrolysis and other emerging approaches—can produce hydrogen using renewable and nuclear power, and other chemical processes can be used to produce hydrogen directly from biomass and waste-stream resources. For example, large-scale centralized hydrogen production could be co-located with current nuclear facilities, which are shown in Figure 8. Hydrogen production from wind power and solar photovoltaics, as shown in Figures 9 and 10, offers a wide geographical range of options for both central 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 (see Figure 11), the resource potential for solid biomass is predominantly in the central and eastern regions (see Figure 12).

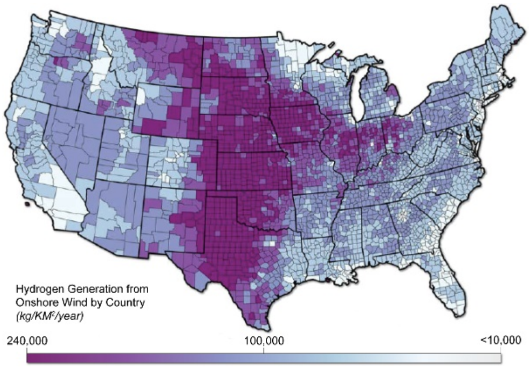

Figure 9. Hydrogen production potential from onshore wind resources, by county land area[35]

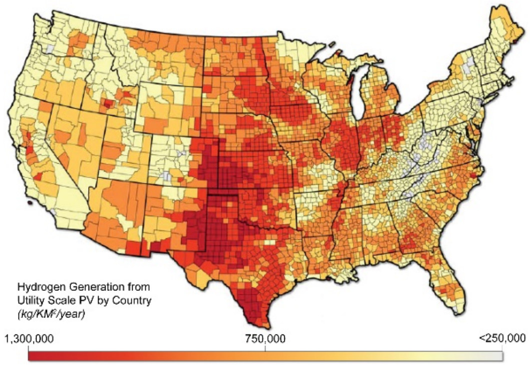

Figure 10. Hydrogen production potential from utility-scale PV, by county land area[36]

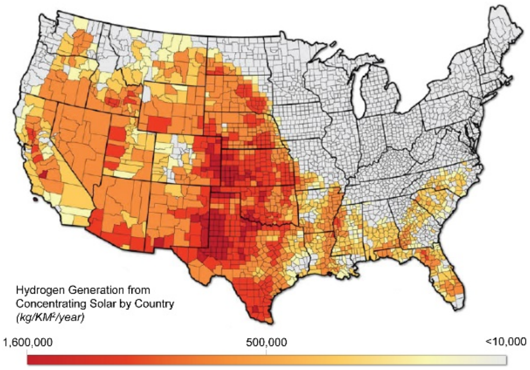

Figure 11. Hydrogen production potential from concentrated solar power, by county land area[37]

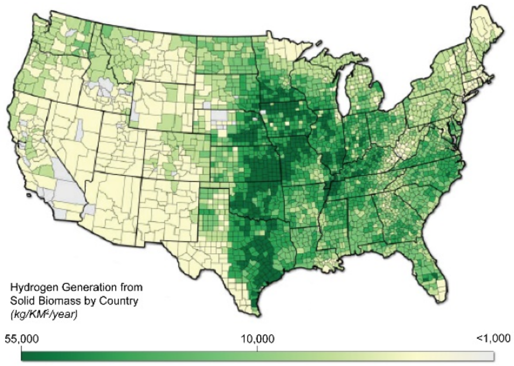

Figure 12. Hydrogen production potential from solid biomass resources, by county land area[38]

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[34] Map created by NREL (July 2020). Data sources: Nuclear power plant operating capacity from U.S. NRC Information Digest (NUREG-1350, Vol 34). Plant status based on EIA *Annual Energy Outlook 2018* https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf and media reports.

[35] Connelly, et al, 2020, op. cit.

[36] Connelly, et al, 2020, op. cit.

[37] Connelly, et al, 2020, op. cit.

[38] Connelly, et al, 2020, op. cit.

In addition to hydrogen production resources, the United States has over 1,600 miles of hydrogen pipelines and three caverns that can store thousands of tonnes of hydrogen. There are also eight liquefaction plants nationwide, with a cumulative capacity of more than 200 metric tonnes/day.[40] Three additional plants have been announced by industry in the last two years.

There is also growing interest in using hydrogen for the production of synthetic fuels, through reaction with carbon dioxide. Accordingly, the idea of co-locating hydrogen production facilities with CCUS facilities is being considered, to help reduce costs and foster regional market opportunities. A snapshot of current carbon storage locations is shown in Figure 13.

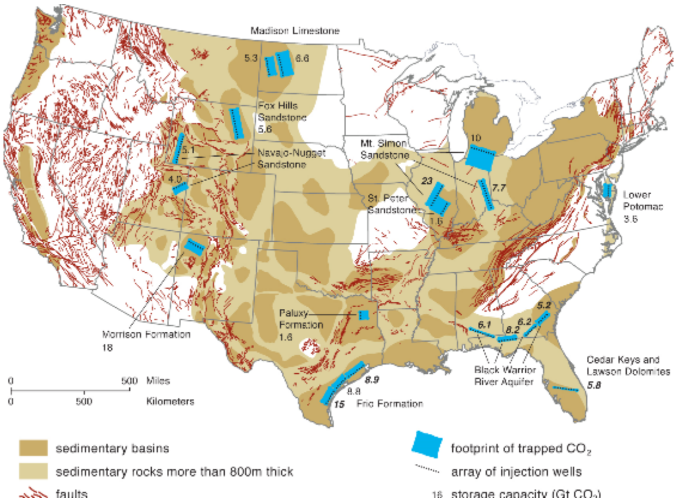

Figure 13. CCS Facilities in the United States[39]

In summary, as shown through the maps in this section, there are extensive opportunities to produce hydrogen from diverse domestic resources, and the Program has identified opportunities for using that hydrogen across multiple applications and sectors. Potential consumption by location is shown below in Figure 14, as analyzed with input from industry stakeholders. Subsequent chapters of this document will outline the Program's strategy and R&D thrusts for each key focus area.

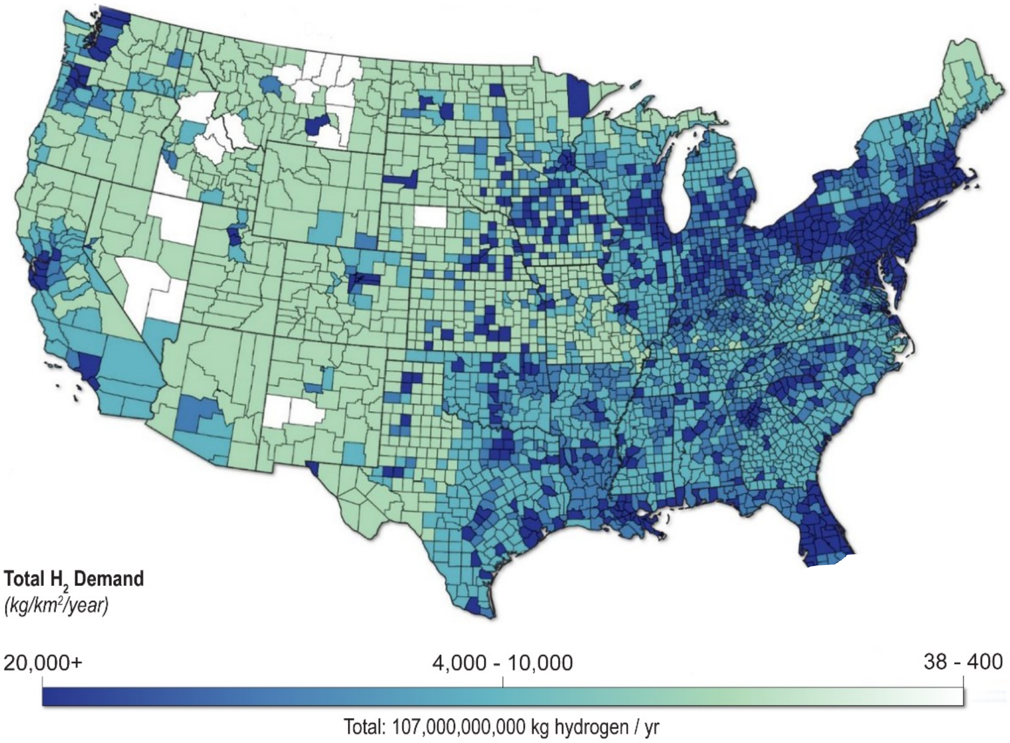

Figure 14. Serviceable consumption potential for hydrogen in the industrial and transportation sectors, natural gas, and storage[41]

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[39] Szulczewski, Michael L., C. MacMinn, H. J. Herzog, and R. Juanes. "Lifetime of carbon capture and storage as a climate-change mitigation technology." Proceedings of the National Academy of Sciences April 3, 2012 109 (14) 5185-5189. https://doi.org/10.1073/pnas. 1115347109

[40] IHS Markit. 2020. "Chemical Economics Handbook: Hydrogen." The total of eight plants includes one additional liquefaction plant in Charleston, Tennessee, which came on line in 2019 and is producing ~5,400 kg/day.

[41] Ruth, et al, 2020, op. cit. (Based on analysis conducted by national labs with industry input over the last two years. Includes ammonia, metals, biofuels, natural gas, synthetic hydrocarbons, refineries, grid storage, and light- medium, and heavy-duty FCEVs).

Program Strategy

DOE is funding RD&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 Program aims to advance hydrogen and related technologies for a wide variety of applications, with varying timeframes 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 shown in Figure 15. More-detailed, technology- and application-specific targets and milestones are included in each office's multi-year 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. Examples include:

- $2/kg for hydrogen production and $2/kg for delivery and dispensing for transportation applications
- $1/kg hydrogen for industrial and stationary power generation applications
- Fuel cell system cost of $80/kW with 25,000-hour durability for long-haul heavy-duty trucks
- On-board vehicular hydrogen storage at $8/kWh, 2.2 kWh/kg, and 1.7kWh/l
- Electrolyzer capital cost of $300/kW, 80,000 hour durability, and 65% system efficiency
- Fuel cell system cost of $900/kW and 40,000 hour durability for fuel-flexible stationary high-temperature fuel cells

Figure 15. Examples of key DOE Hydrogen Program targets

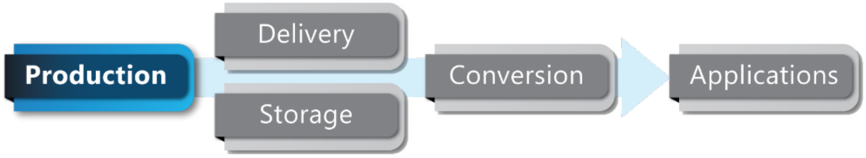
The Program is addressing key challenges to achieving the H2@Scale vision by conducting activities to:

- 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
- 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 chapter in the *Plan* provides additional details on the current status and needs in the key areas of RD&D that the Program is pursuing, namely Hydrogen Production, Delivery, Storage, Conversion, and Applications.

3 Technology Focus Areas & RD&D Thrusts

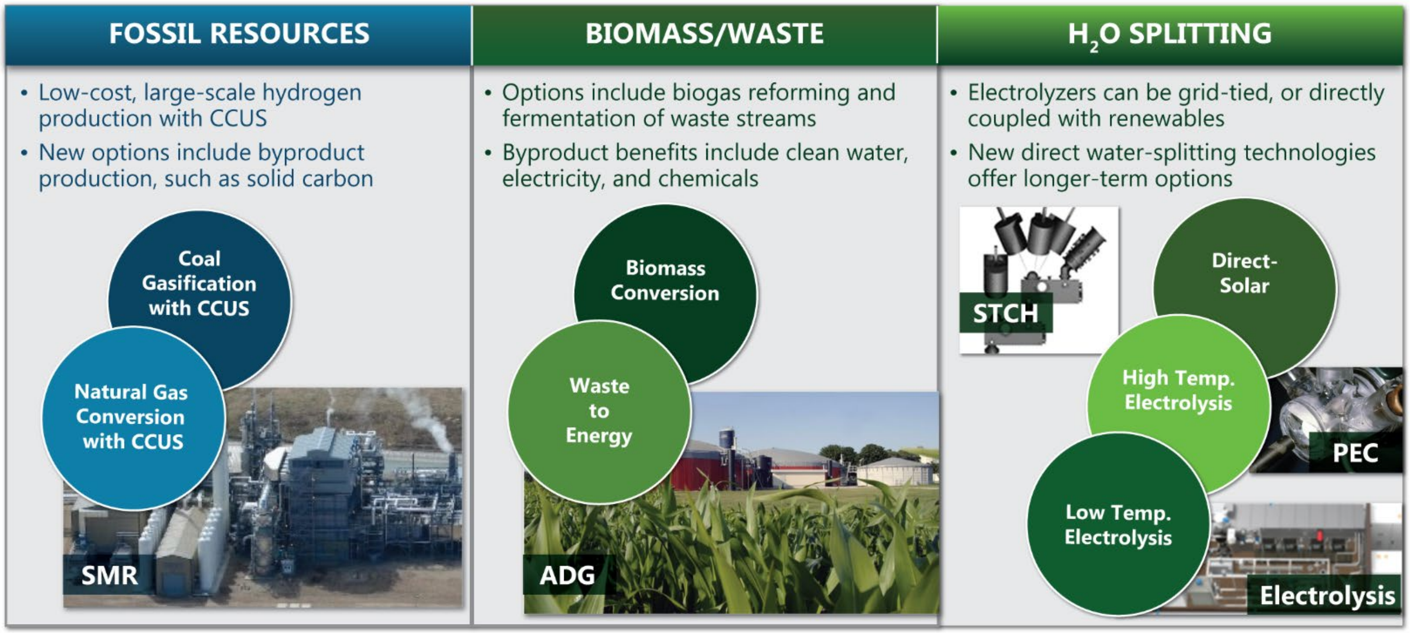
Hydrogen Production



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 carbon-neutral hydrogen production. Global demand for hydrogen across sectors is increasing, with a current worldwide consumption at approximately 70 million metric tonnes (MMT) per year.[42] Of this, the United States currently produces and consumes almost 10 MMT annually, equivalent to just over 1 quadrillion BTUs per year (1% of U.S. energy consumption).[43]

To meet this growing demand, a broad portfolio of hydrogen production pathway technologies are being explored and developed. As shown in Figure 16, these include technologies for: tapping into fossil resources with CCUS; extracting hydrogen from biomass and waste-stream resources; and splitting water.[44] This wide range of options opens regional opportunities to expand the hydrogen supply base across the country, offering carbon-neutral hydrogen production capacities from a few hundred to hundreds of thousands of kilograms per day.


FOSSIL RESOURCES

- Low-cost, large-scale hydrogen production with CCUS
- New options include byproduct production, such as solid carbon

BIOMASS/WASTE

- Options include biogas reforming and fermentation of waste streams
- Byproduct benefits include clean water, electricity, and chemicals

H_2O SPLITTING

- Electrolyzers can be grid-tied, or directly coupled with renewables
- New direct water-splitting technologies offer longer-term options

Figure 16: Diverse hydrogen production technologies[45]

(SMR= steam methane reforming; CCUS= carbon capture, utilization, and storage; ADG= anaerobic digester gas; STCH= solar thermochemical hydrogen; PEC= photo-electrochemical water splitting)

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[42] U.S. Department of Energy. October 2019. Hydrogen and Fuel Cells Program Record 19002. "Current Hydrogen Market Size: Domestic and Global." https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf.

[43] U.S. Department of Energy, October 2019, op. cit.

[44] U.S. Department of Energy. 2015. "Quadrennial Technology Review 2015. Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels, Hydrogen Production and Delivery." https://energy.gov/sites/prod/files/2015/11/f27/QTR2015-7D-Hydrogen-Production-and-Delivery.pdf.

[45] Randolph, Katie. "HydroGEN: Accelerating Advanced Water Splitting Materials Discovery & Development," 231st Electrochemical Society Meeting, New Orleans, LA. May 28 – June 1, 2017.

Fossil Resources

Fossil fuels such as natural gas or coal 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 steam-methane-reforming (SMR) in large central plants fed by the existing natural gas infrastructure. Partial oxidation of natural gas (or other hydrocarbons), autothermal reforming (converting natural gas, steam, and oxygen to syngas), and gasification of coal (or coal/biomass/waste-plastic blends)—all with CCUS—are other options leveraging domestic resources. Combining fossil-based processes with CCUS offers a promising near-term option for carbon-neutral 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. Other emerging approaches include the direct pyrolysis of methane into hydrogen and solid carbon co-products. Advanced production systems have been developed that are capable of producing carbon free 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. While SMR and gasification with CCUS are mature industrial technologies that can produce hydrogen for a cost of less than $2/kg today, ongoing RD&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. Research advances in gasification and reforming technologies with CCUS, including reductions in capital and operating costs, target carbon-neutral hydrogen production at less than $1/kg.

Biomass and Waste-Stream Resources

Domestic biomass and waste-stream resources, with the potential for over a billion dry tons of feedstock annually,[46] 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.[47] 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 non-thermal 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, RD&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 pre-treating and transporting feedstocks.

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[46] U.S. Department of Energy. 2016. "2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks." M.H. Langholtz, B.J. Stokes, and L.M. Eaton (Leads). ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651. https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf.

[47] National Research Council and National Academy of Engineering. 2004. "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs." (Washington, DC: National Academies Press), http://www.nap.edu/openbook.php?isbn=0309091632.

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 (such as solar, wind, nuclear, and others). Low-temperature electrolyzers (including liquid-alkaline and membrane-based electroyzers) that use electricity to split water offer near-term commercial viability, with units available today at the multi-megawatt (MW) scale.

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 hydrogen produced from low-temperature electrolysis depends strongly on the electricity cost: it currently ranges from \$5–\$6/kg-H_2 for electricity pricing in the \$0.05–\$0.07/kWh range.[48] The availability of lower-cost electricity—for example, in the \$0.02–\$0.03/kWh range from emerging wind and solar assets—coupled with ongoing advancements in electrolyzer technologies offers a pathway to cost-competitive hydrogen, at less than \$2/kg.[49] However, more work is needed to achieve consistent, widely available low-cost and low-carbon electricity, and RD&D is still required to reduce the cost and improve the efficiency and durability of electrolyzers. High-temperature electrolyzers can leverage both electricity and heat from generation sources such as nuclear, fossil with CCUS, or concentrated solar power plants to improve conversion efficiencies, further reducing cost. Reversible fuel cells, currently under development, combine the functionality of electroyzers 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 including solar thermochemical systems, as well as light-driven photoelectrochemical processes. Ongoing RD&D—at the materials, component, and system levels—will be needed to address efficiency, durability, and cost challenges in all water-splitting processes.

Hydrogen Production Target

Affordable hydrogen from diverse domestic resources:

- <\$2/kg for transportation end uses
- <\$1/kg for industrial and bulk power/polygeneration applications

Common RD&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 (ATR)
- 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

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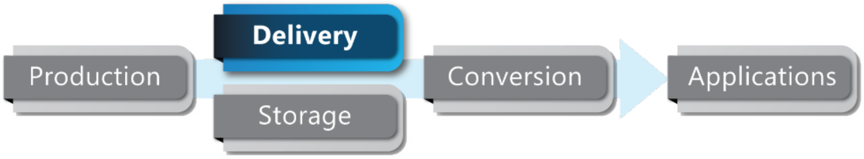
[48] U.S. Department of Energy. September 2020. Hydrogen and Fuel Cells Program Record 20004. "Cost of Electrolytic Hydrogen Production with Existing Technology." https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[49] U.S. Department of Energy. February 2020. Hydrogen and Fuel Cells Program Record 19009. "Hydrogen Production Cost From PEM Electrolysis -2019." https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdfy.

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.

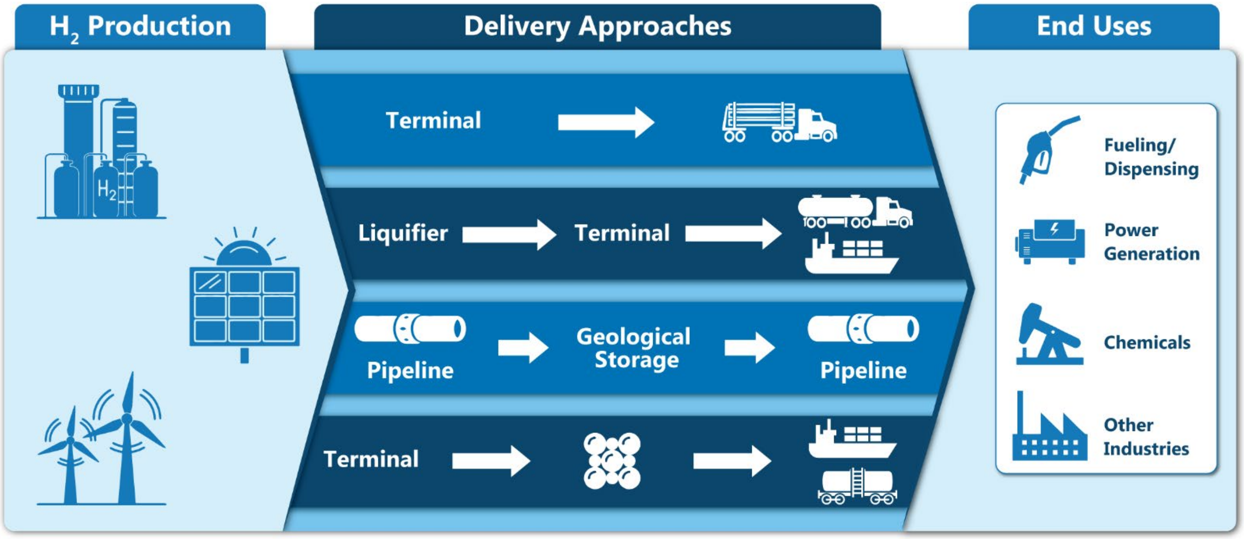


Figure 17. The four main methods of hydrogen delivery: gaseous tube trailers, liquid tankers, pipelines, and chemical hydrogen carriers

As shown in Figure 17, 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. RD&D efforts will be needed to enhance the lifetime of pressure vessels onboard tube trailers, reduce the cost of high-pressure composite tube trailers, and increase the capacity of compressors used at tube trailer terminals.

Pipelines

Hydrogen pipelines are often used in regions where there is significant demand (thousands of tonnes/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, and these are mostly concentrated on 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. RD&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 co-mingled with natural gas, “city gas,” or other products, is also possible as the economy builds demand. Some applications can use blends of hydrogen, while other applications may require separation of hydrogen and natural gas at the end use, as described further in the Applications section of this chapter.

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 onboard marine vessels are also being explored for international shipping of low-carbon hydrogen for export markets. Liquid tankers commonly store more than five 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 six to 30 tonnes/day.[50] 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 pre-cooled 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, RD&D is needed to enable novel non-mechanical 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.

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-

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[50] IHS Markit, 2020, op. cit.

way carriers. One-way carriers are materials that do not release a by-product for re-use or disposal after the hydrogen is released (such as ammonia). Two-way carriers are those whose by-products are typically returned for processing for reuse or disposal after the hydrogen is released (such as methylcyclohexane/toluene). The use of chemical hydrogen carriers is in the early stages of commercialization and RD&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—e.g., the fueling pressure is typically 700 bar (approximately 10,000 psi or 70 MPa)—and the technologies are commercially deployed in more than 45 retail hydrogen fueling stations for light-duty fuel cell electric vehicles (FCEVs) in the United States. For medium- and heavy-duty FCEVs, 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:

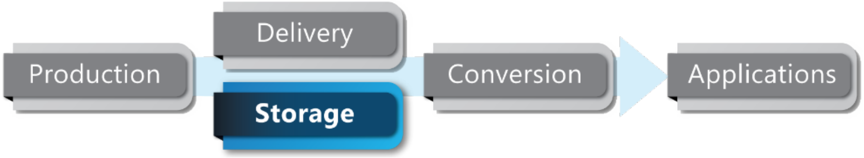
- <$5/kg for transportation end uses in early markets
- <$2/kg for ultimate market expansion for high value products

RD&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 will 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/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 of this chapter.

Common RD&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, 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 three times the energy content of gasoline per unit of mass,[51] 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 18.

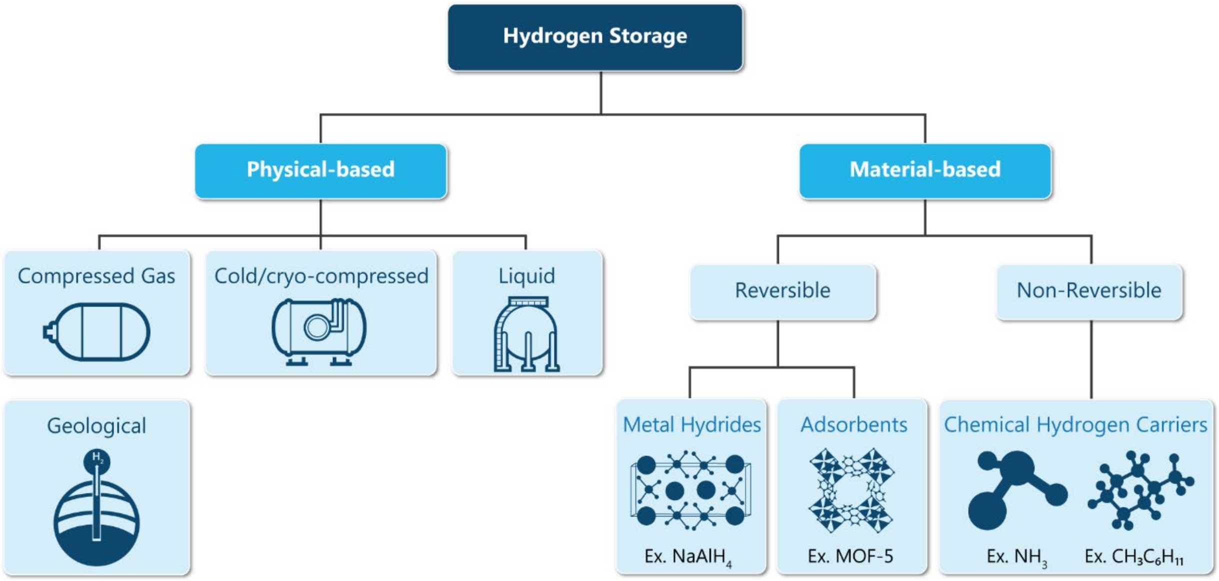


Figure 18. Current portfolio of hydrogen storage options

Includes physical-based gaseous and liquid storage in tanks, and reversible and non-reversible materials-based storage.[52] 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 and 700 bar[53] 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.

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

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

[53] 350 bar and 700 bar correspond to 5,076 pounds per square inch (psi) and 10,153 psi, respectively.

One example is the industrial-scale hydrogen-storage salt cavern located in Beaumont, Texas, which currently serves as a buffer in the Gulf Coast hydrogen pipeline system.

Additional RD&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.[54] 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.[55] 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 RD&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 micro-porous super activated carbons or metal-organic frameworks (MOFs), utilize weak bonding between molecular hydrogen and adsorbent surfaces, and typically require lower storage temperatures. Hydrogen storage via metal hydrides and adsorbents is considered reversible, since hydrogen uptake and release can be controlled by changing the temperature and/or the pressure. Many chemical hydrogen carriers, 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 RD&D

Example: Hydrogen Storage Targets

- Onboard hydrogen storage systems for transportation: $8/kWh stored at 2.2 kWh/kg and 1.7 kWh/L
- Rechargeable portable power systems: $0.5/kWh stored at 1.0 kWh/kg and 1.3 kWh/L
- High-volume cost of high-strength carbon fiber for tanks: $13/kg[56]

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[54] For reference the energy density of liquid hydrogen (71 g/l) is equivalent to 2. 4 kWh/l.

[55] The scale of liquid hydrogen storage vessels for different industrial end uses ranges from hundreds of gallons up to more than a million gallons.

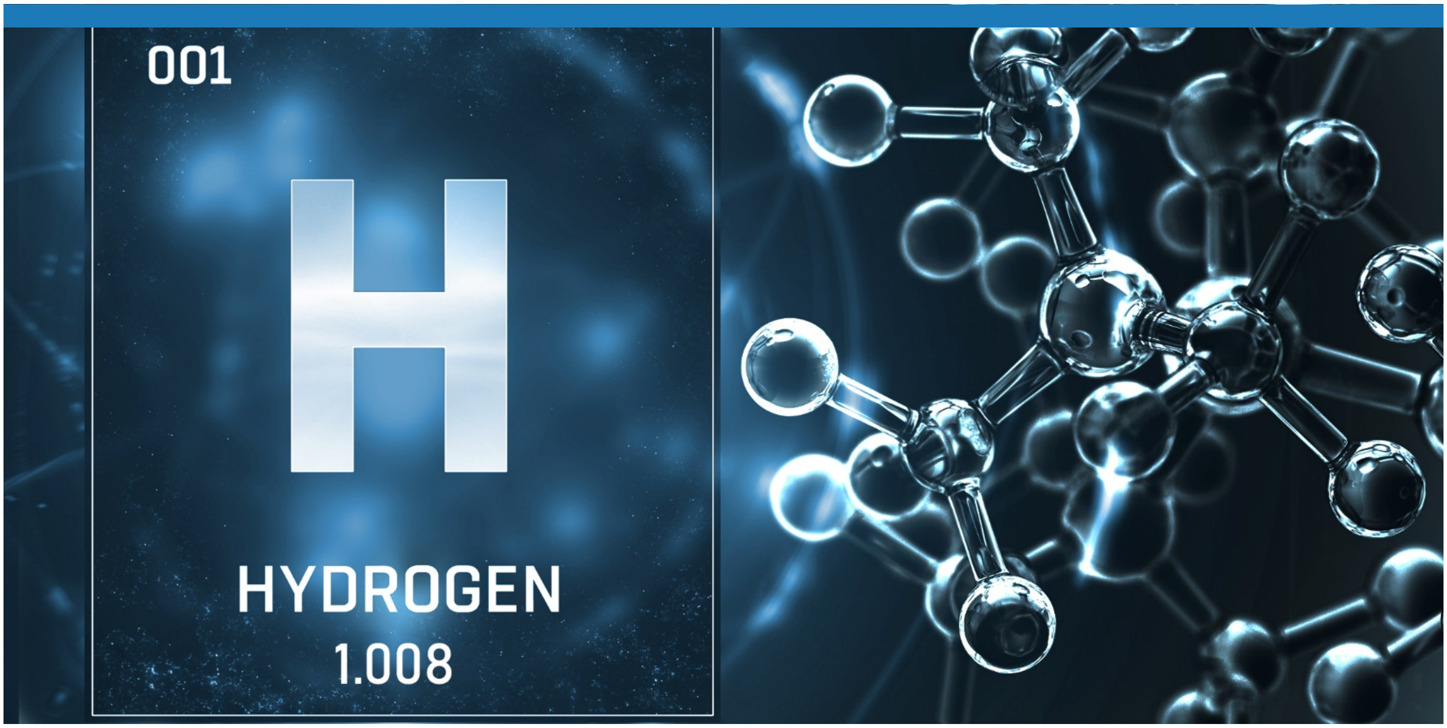
[56] Target based on small-scale onboard storage tanks (5.6 kg-H_2); the cost of carbon fiber becomes less crucial for larger systems as they require less carbon fiber per kg H_2.

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

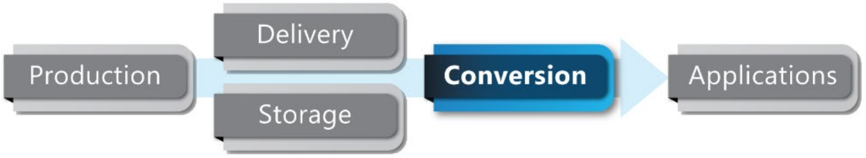
The most suitable type of storage will depend on a number of factors such as the end-use application, the amount of hydrogen needed, geographical and geological constraints, and the required flow rates. For instance, a 500-MW turbine operating on hydrogen will require approximately 500–600 tons of hydrogen per day, over 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 onsite for two days of back-up power). Today's long-haul fuel cell truck manufacturers are targeting stations with a few tons per day of hydrogen. On-board storage can range from a few grams for small-scale drones, a hundred kilograms for fuel cell trucks, and over a ton for certain marine and rail applications. Examples of key targets and RD&D thrusts to address key hydrogen storage challenges are shown here.

Common RD&D Thrusts for Hydrogen Storage

- Reduced costs, at the material-based, component-, and system-level
- Low-cost, high-strength carbon-fiber for high-pressure tanks
- Materials compatible with hydrogen for durability and safety
- Cryogenic RD&D for liquid hydrogen and cold/cryo-compressed storage
- Discovery and optimization of hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements
- Optimization for round-trip efficiency using chemical hydrogen carriers
- Storage of hydrogen in the form of a chemical energy carrier that can be used in hydrogen turbines
- Identification, assessment, and demonstration of geologic storage of hydrogen
- 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 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.

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 the National Aeronautics and Space Administration, which has used hydrogen in the space shuttle's main engines, 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 aero-derivative machines, and at concentrations of up to 50% in large-frame combined-cycle turbines.[57] 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 RD&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)

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[57] J. Goldmeer. 2019. "Power to Gas: Hydrogen for Power Generation. Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem." https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf.

Though significant progress has been made, additional RD&D is needed to address issues such as auto-ignition, flashback, thermo-acoustics, 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 will allow for limiting NO_x emissions to single digit (ppm) levels, improved flame detection, and monitoring for flashback and thermo-acoustic instabilities. NO_x emissions control while firing hydrogen requires micromixer combustor technology, which is a refinement of today's pre-mixed 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.

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 over 60% have been demonstrated,[58] and over 80% efficiency[59] is possible when fuel cells are used in combined heat and power applications.

Example: 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 may 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 many megawatts for large-scale stationary power.

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[58] 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." Argonne National Laboratory. ANL/ESD-18/12 https://publications.anl.gov/anlpubs/2018/06/144774.pdf.

[59] U.S. Department of Energy. September 2011. Hydrogen and Fuel Cells Program Record 11014. "Medium-scale CHP Fuel Cell Systems Targets." https://www.hydrogen.energy.gov/pdfs/11014_medium_scale_chp_target.pdf; and Doosan. 2018. "PureCell Model 400." http://www.doosanfuelcellamerica.com/download/pdf/catalog/pafc-400kw_us_en.pdf.

Common RD&D Thrusts for PEMFCs

- Reduce platinum group metal catalyst loading, through materials R&D
- High-temperature tolerant, low-cost, and durable membranes
- Improved component-design and materials integration to optimize manufacturable and scalable electrode structures for membrane electrode assemblies
- Internal reforming of carbon neutral fuels for directly fed fuel cells
- Accelerated stress tests, improved understanding of degradation mechanisms, and mitigation approaches
- Improved balance-of-plant (BOP) 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.

Example: SOFC Target for Stationary Power Generation

- $900/kW fuel cell system cost
- 40,000 hour durability

Polymer electrolyte membrane fuel cells (PEMFCs) 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 start-up 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 start-up challenging. There are also intermediate temperature fuel cells such as *molten carbonate* (600-700°C) and *phosphoric acid fuel cells* including polymer-phosphoric acid-based systems (150-200°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 RD&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 RD&D plans of the individual program offices.

Common RD&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 BOP systems integration, controls, and optimization for load following and modular applications
- Improved BOP 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 19, fuel cells can use a wide range of fuels and feedstocks, and can provide power for a number of applications across multiple sectors. In addition to these applications, DOE is exploring the use of fuel cells for tri-generation, which can use fuels such as coal syngas, biogas, or natural gas to co-produce 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 of this chapter, in *electrolysis mode*, a reversible fuel cell uses electricity and water to produce hydrogen; and in *fuel-cell mode*, they use 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 a 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.

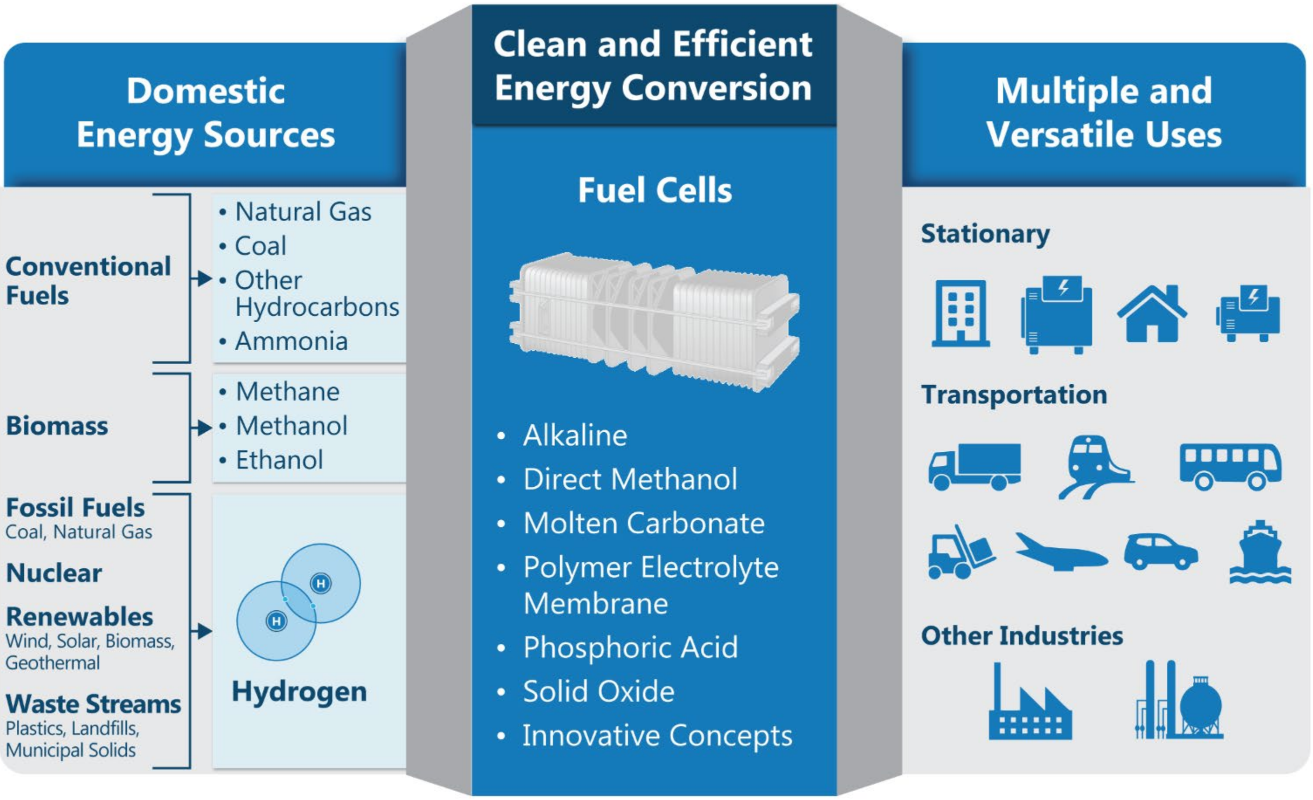
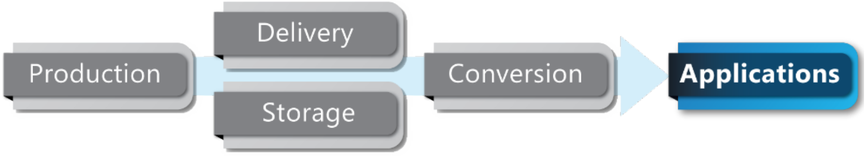


Figure 19. Versatility of fuel cells

For all these applications, there is a common need to reduce cost and improve durability, 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 RD&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. Reliable and low cost balance-of-plant components such as compressors, blowers, and power electronics are also required.

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 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 more than a third of U.S carbon dioxide emissions[60] and can be a key contributor to localized air pollution. 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 other medium- and heavy-duty vehicles that require longer driving ranges, involve heavy loads, or demand faster refueling times than may be available with battery electric vehicles alone. With increased urgency to reduce emissions and energy-related expenses, significant opportunities exist, as the medium- and heavy-duty sector accounts for 25% of annual vehicle fuel use even though it is only 4% of the vehicle fleet.[61]

In addition to its use in fuel cells, hydrogen can also be 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.

The forklift and material-handling industry is an example of an early market successes for hydrogen fuel cells in transportation, where DOE's early investment over a decade ago has now led to over 35,000 systems commercialized by the private sector (as of 2020) without any further DOE funding. Hydrogen is also already being used in more than 8,800 passenger and commercial vehicles, with a growing infrastructure of approximately 45 hydrogen fueling stations in the United States.[62,63] With over 25,000 fuel cell vehicles and more than 470 fueling stations worldwide,[64] the United States is already a major player in this emerging market.

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[60] U.S. Energy Information Administration. "Today in Energy." March 19, 2019. Accessed online: https://www.eia.gov/todayinenergy/detail.php?id=38773.

[61] Oak Ridge National Laboratory. 2017. "Transportation Energy Data Book 36." Tables 4.1, 4.2, 5.1, and 5.2. https://info.ornl.gov/sites/publications/Files/Pub104063.pdf.

[62] California Fuel Cell Partnership, 2020, Hydrogen Stations List. Development Status of Hydrogen Stations in California. Accessed online: https://cafcp.org/sites/default/files/h2_station_list.pdf.

[63] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. 2020. Alternative Fuels Data Center, "Hydrogen Fueling Station Locations." Accessed online: https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY.

[64] International Energy Agency. 2020. "Hydrogen". Accessed online: https://www.iea.org/reports/hydrogen.

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 (IMO) limit the sulfur content in fuel oil used on ships (or "bunker fuel") from 3.5% to 0.5%, starting in 2020.[65] 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.[66] 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.[67] 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 of 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 liquid or solid 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.[68] 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,[69] 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 operational facilities in Austria and Sweden.

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,[70] 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

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[65] The Maritime Executive. 2018. "IMO Answers Questions on the 2020 SOx Regulation. Accessed online: https://www.maritime-executive.com/article/imo-answers-questions-on-the-2020-sox-regulation.

[66] Merk, O.. 2014. "Shipping Emissions in Ports," p. 15. International Transport Forum. Accessed online: https://www.itf-oecd.org/sites/default/files/docs/dp201420.pdf.

[67] International Energy Agency. "The Future of Hydrogen. Seizing Today's Opportunities," June, 2019. Accessed online: https://www.iea.org/reports/the-future-of-hydrogen. The 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.

[68] According to the International Energy Agency, 2019, op. cit., oil refining and ammonia production use ~69MMT of hydrogen annually, accounting for a significant percentage of the global consumption.

[69] World Steel Association. 2020. "Steel;s Contribution to a Low Carbin Future and Climate Resilient Societies."Accessed online: https://www.worldsteel.org/en/dam/jcr:7ec64bc1-c51c-439b-84b8-94496686b8c6/Position_paper_climate_2020_vfinal.pdf.

[70] J. Lehne and F. Preston. 2018. "Making Concrete Change. Innovation in Low-carbon Cement and Concrete." Chatham House Report. Accessed online: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf.

methanol or renewable natural gas; as well as 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 DRI (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 (CHP), and backup power. As noted in the previous chapter, 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 multi-megawatt 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 300,000 residential fuel cells are operating in Japan[71] to provide reliable power and hot water in homes, and more than 8,000 PEM fuel cells have been deployed for backup power in the United States,[72] primarily for telecommunications towers. In 2018, over 220 MW of stationary fuel cell systems were sold worldwide.[73] 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 RD&D is needed for qualification in utility-scale power generation. Additional RD&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.

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 (HES) combines electricity generation,

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[71] International Partnership for Hydrogen and Fuel Cells in the Economy. March 2020. "Summary Country Update March 2020: Japan." https://www.iphe.net/japan.

[72] Open Access Government. December 6, 2019. "Fuel cells: Delivering reliable power when needed for emergency response efforts." https://www.openaccessgovernment.org/fuel-cells-reliable-power-emergency-response/79014/#:~:text=Currently%2C%20there%20are%20more%20than%208%2C500%20fuel%20cell,simple%20infrastructure%20like%20traffic%20lights%20has%20real%20ramifications.

[73] E4Tech, 2019, op. cit.

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 standalone alternatives, as shown in the example in Figure 20. Hydrogen technologies integrated in an HES offer unique benefits in both on-grid and off-grid electric-power applications. Examples include: mid- to long-duration/seasonal energy storage;[74] grid leveling and stabilization services that leverage the fast-acting dynamic response of electrolyzers;[75] and the ability to co-produce (along with electricity) hydrogen or other hydrogen-based fuels, chemicals, or products for use in diverse markets, potentially at higher value than electricity.[76] Multiple hybrid scenarios are being explored that could optimally leverage the benefits of integrated energy systems; some key examples are described below.

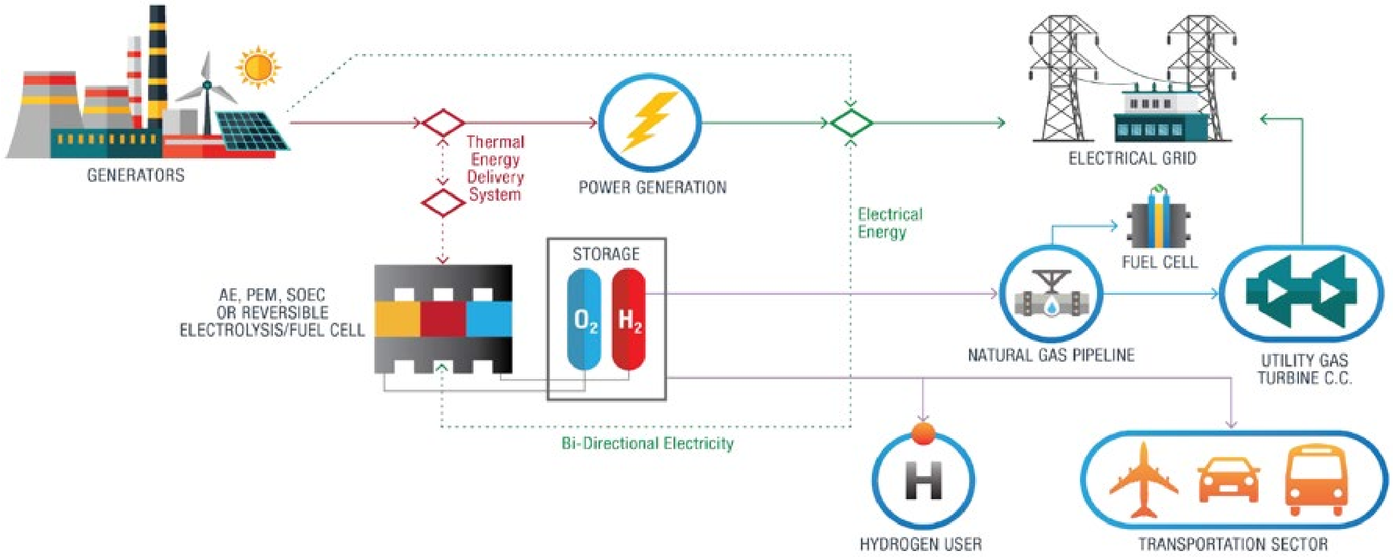

Figure 20. Example hybrid hydrogen energy system[77]

Grid Integration & 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 bi-directional 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, for example through injection into the natural gas pipeline infrastructure, or through onsite co-production 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.[78] Techno-economic analysis is being conducted, in collaboration with electric utilities, to identify optimal configurations for integrating electrolyzers with renewables in grid, micro-grid, and off-grid applications.[79]

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[74] Hunter, Chad, E. Reznicek, M. Penev, J. Eichman, S. Baldwin. May 2020. "Energy Storage Analysis." National Renewable Energy Laboratory. https://www.hydrogen.energy.gov/pdfs/review20/sa173_hunter_2020_o.pdf.

[75] Kurtz, Jennifer, K. Harrison, R. Hovsapian, M. Mohanpurkar. 2017. "Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TV031." Accessed online: https://www.hydrogen.energy.gov/pdfs/review17/tv031_hovsapian_2017_o.pdf.

[76] Ruth, et al., 2020, op. cit.

[77] Applied Energy Tri-Lab Consortium (Idaho National Laboratory, National Energy Technology Laboratory, and National Renewable Energy Laboratory). Internal DOE presentation, 2019.

[78] Hovsapian, Robert, J. Kurtz, M. Panwar, A. Medam and C. Hanson. 2019. "Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TA015." Accessed online: https://www.hydrogen.energy.gov/pdfs/review19/ta015_hovsapian_2019_o.pdf.

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

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 steam methane reforming of natural gas with vacuum-swing adsorption to co-produce 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 poly-generation 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 RD&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, utlize unused energy, and provide an additional revenue stream. For context, as one example, a 1-GW nuclear power plant can produce about 41,000 tonnes of hydrogen in a year, assuming the plant produces electricity for 70% of the time and hydrogen for 26% of the time (with 4% downtime for maintenance).[80] Leveraging nuclear-generated electricity and heat, hydrogen can be efficiently produced using low- or high-temperature electrolyzer technologies, and utilized onsite to service hydrogen needs of the nuclear plant (e.g., in turbine generator cooling), or exported/monetized for other end uses. While nuclear hybrid systems are not yet ready for full-scale commercial deployment, 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, techno-economic analysis—including market assessments for a number of specific nuclear power plants—has identified the potential economic benefits of producing hydrogen through different onsite electrolyzer options, including those currently being pursued via pilot projects and other technologies. Ongoing materials-, component-, and system-level RD&D are also continuing in support of various nuclear/hydrogen approaches. Along with the continued development of both low- and high-temperature electrolyzers, design optimization of fully integrated nuclear hybrid systems will help to addresses performance, durability, and cost, as well as safety and risk issues. There are also ongoing projects that support system validation in simulated and real-world operations.

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 RD&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, 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.

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[80] Assumes an electrolyzer electrical conversion efficiency of 55kWh/kg, consistent with the state-of-the-art in PEM electrolysis, as documented in DOE Hydrogen Program Record #19009, "Hydrogen Production Cost From PEM Electrolysis – 2019," February 2020, https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf. Calculation: (1,000,000 kW x 8760 hours/yr *26%) / 55 kWh/kg = 41,141,090 kg/yr = ~41,411 tonnes/yr.

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 will 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—RD&D efforts will be needed to overcome technical challenges and accelerate progress.

By developing processes and technologies specifically tailored to high-volume manufacturing, RD&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 development of:

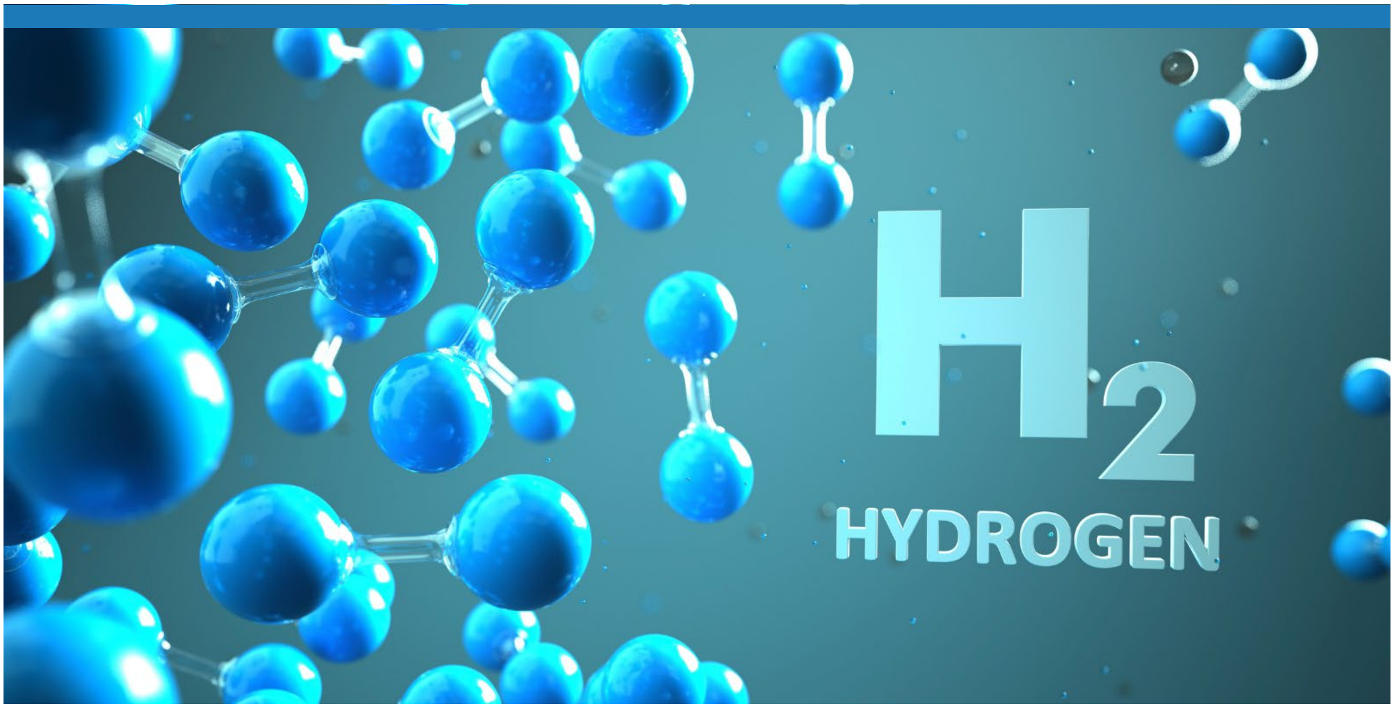
- High-speed manufacturing techniques for processes such as forming, stamping, molding, sealing, joining, coating, and roll-to-roll processing
- Best practices for material and component handling
- Additive and automated manufacturing/assembly processes
- Technologies for in-line diagnostics and quality 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 as 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.

RD&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 (such as reforming, coal gasification, refineries, etc.), 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.

Common RD&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, as well as in 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 & 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 Program actively solicits input to incorporate in the planning of its activities. Among the primary channels for this input are *requests for information* (RFIs) and *workshops* conducted by DOE to help establish high-level program direction and to develop and update technology-specific RD&D plans. The Program also regularly conducts workshops for specific technology areas, to identify and update RD&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 Program's activities are funded using various competitive mechanisms, including *funding opportunity announcements* (FOAs), 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* (CRADAs) to encourage partnerships between the private sector and national labs for joint development and *strategic partnership projects* (SPPs)[81] through which industry can contract company-specific tasks to be conducted at national labs.

DOE has invested more than $4 billion over the last 20 years in various areas such as advanced water splitting to produce hydrogen from renewable and nuclear sources, advanced gasification and turbines to produce and use hydrogen from fossil fuels, and diverse fuel cell technologies for multiple applications. Through these and ongoing programs, all DOE offices use competitive FOA 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 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, and the scientific research community
- *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 RD&D progress under the partnership with U.S. DRIVE (see more in "Private Sector and

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[81] Formerly known as Work for Others (WFOs) throughout DOE.

Other Non-Governmental Partnerships" below); input and advice from the Hydrogen and Fuel Cell Technical Advisory Committee,[82] other government agencies, congressionally requested reviews,[83,84] and comprehensive project reviews by more than 200 technical experts at the Program's Annual Merit Review and Peer Evaluation Meeting[85]

- *Down-selection 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 on-board vehicular fuel processing, sodium borohydride hydrolysis, and carbon nanotubes for onboard vehicular hydrogen storage.

Internal & 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 over two decades, multiple offices are engaged either directly or indirectly in hydrogen-related activities. Figure 21 shows the key offices involved: EERE, FE, NE, OE, SC, and ARPA-E. The Hydrogen and Fuel Cells Coordination Group coordinates Program activities among the DOE offices and meets monthly 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 FOA processes and project execution both through their field offices and procurement functions and, in some instances, through direct projects at national laboratories. The offices coordinate on FOA 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 3.

The Program also coordinates with crosscutting offices including the Office of Technology Transitions (OTT) and the Loan Program Office (LPO).

- OTT, which was established in 2015, focuses on enabling technology transfer and expanding the commercial impact of DOE's RD&D portfolio to advance the economic, energy, and national security interests of the nation. The office develops the Department'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 will 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.

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[82] U.S. Department of Energy. Hydrogen and Fuel Cells Program. "Hydrogen and Fuel Cell Technical Advisory Committee." Accessed online: https://www.hydrogen.energy.gov/advisory_htac.html.

[83] U.S. Department of Energy. August 2019. "Report on the Status of the Solid Oxide Fuel Cell Program. Report to Congress." https://www.energy.gov/sites/prod/files/2019/09/f66/EXEC-2019-002655_Signed%20Report%201.pdf.

[84] U.S. Department of Energy. 2020. DOE Hydrogen and Fuel Cells Program, "DOE Biennial Reports to Congress." Accessed online: https://www.hydrogen.energy.gov/htac_reports.html.

[85] U.S. Department of Energy. Hydrogen and Fuel Cells Program. "Annual Merit Review and Peer Evaluation." Accessed online: https://www.hydrogen.energy.gov/annual_review.html.

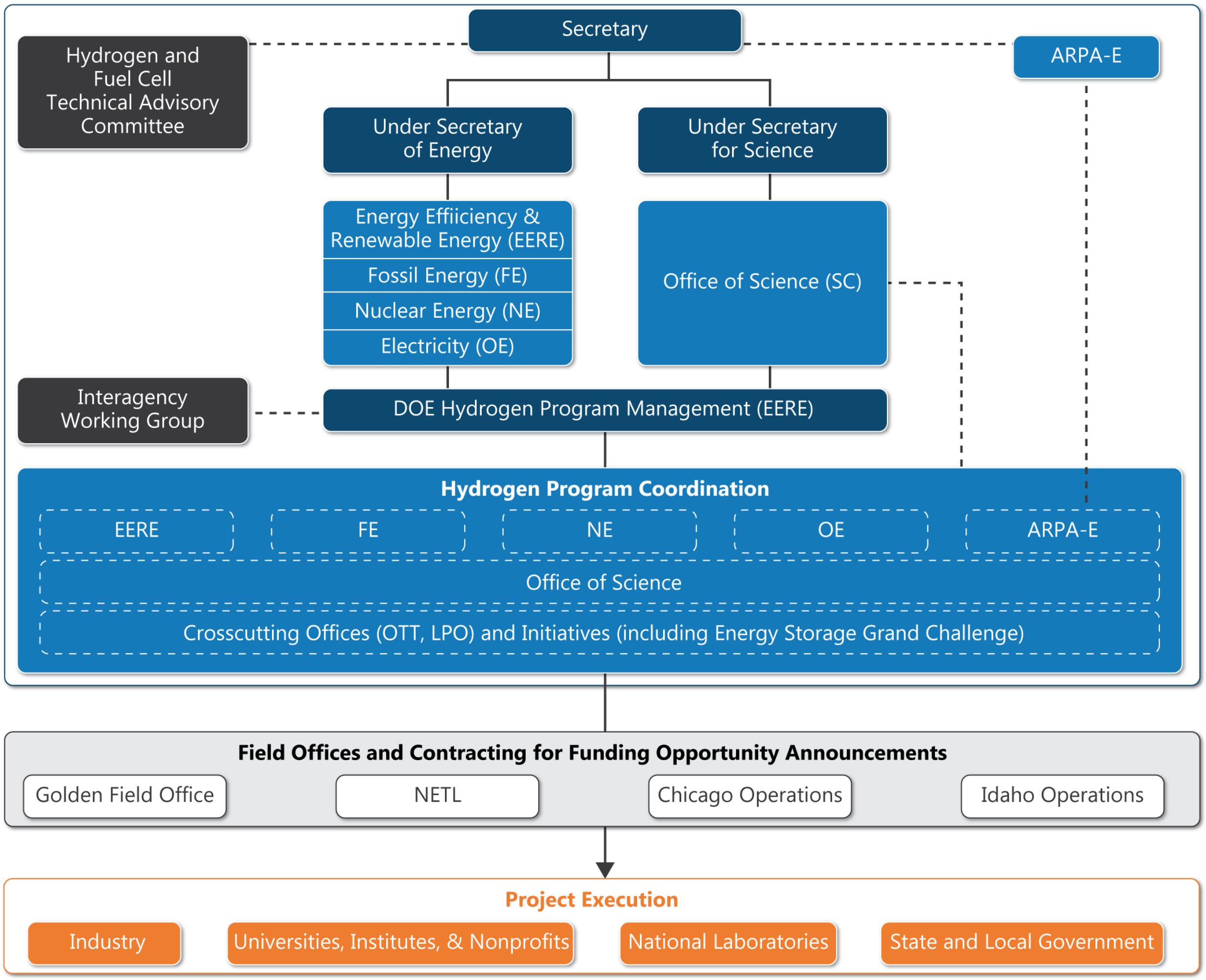

Figure 21. DOE Hydrogen Program organizational structure

- The LPO has a mission to provide access to debt capital to U.S. energy infrastructure projects. LPO's Innovative Energy Loan Guarantee Program currently has over $20 billion in lending capacity for innovative energy projects in the U.S. that reduce greenhouse gas emissions. A wide range of projects could be eligible in the energy efficiency, renewable, advanced fossil and nuclear sectors. LPO financing may be appropriate for projects that are at first commercialization stage or entail first-of-a-kind technology. The objective is to render innovative projects/technology replicable and bankable for future commercial financing. LPO extends loans that are typically structured as limited recourse project financings, and serves as a valuable partner to applicants throughout the entire lifetime of a project. LPO can provide flexible financing that is customized to the specific needs of each project.

In addition, the Hydrogen Program coordinates with crosscutting initiatives and efforts that span multiple offices across DOE, including the Energy Storage Grand Challenge (ESGC), which provides an over-arching strategy for energy storage. The vision for the ESGC is to create and sustain global leadership in energy storage utilization and exports, with a secure domestic manufacturing and supply chain that is independent of foreign sources of critical materials, by 2030.[86] Hydrogen technologies can play a key role and the Program has been actively involved in workshops and analyses through the ESGC.

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[86] U.S. Department of Energy. "About the Energy Storage Grand Challenge." Accessed online: https://www.energy.gov/energy-storage-grand-challenge/about-energy-storage-grand-challenge.

Table 3. Offices engaged in the DOE Hydrogen Program: key activities and focus areas

Office of Energy Efficiency & Renewable Energy (EERE)	Office of Fossil Energy (FE)
The **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 (solar, wind, biomass, geothermal, water power, and renewable hydrogen), energy efficiency in buildings and the industrial sector, transportation technologies across applications (vehicles, trucks, marine, rail, air), advanced manufacturing, and crosscutting activities (the Federal Energy Management, Weatherization, and Intergovernmental Programs). Examples of hydrogen and fuel cell related RD&D include: • The **Hydrogen and Fuel Cell Technologies Office (HFTO),** leading DOE's Hydrogen Program including H2@Scale, supports RD&D and innovation to advance diverse technologies and infrastructure for hydrogen production, delivery, storage, and utilization. HFTO conducts 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 FE on various topics including reversible solid oxide fuel cells; with NE and OE, particularly on integrating renewables into the grid using hydrogen as an energy storage medium; and with SC and ARPA-E on basic science and next generation technologies. • The **Advanced Manufacturing Office (AMO)** 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 like electrolyzers, hydrogen storage tanks, and fuel cells. AMO also supports technical assistance activities enabling the use of fuel cells in combined heat and power systems for industrial and building applications. • The **Bioenergy Technologies Office (BETO)** supports a wide range of RD&D, including technologies that can utilize hydrogen for production of biofuels and bioproducts. BETO's efforts also enable hydrogen production from biomass or bio-waste streams, through various approaches, including the use of advanced electrochemical and microbial processes. • The **Vehicle Technologies Office (VTO)** supports a broad portfolio of next-generation technologies to improve battery-electric and other alternative-fuel vehicles, as well as advanced combustion engines. VTO's efforts include overall vehicle efficiency improvements (e.g., light-weighting) as well as onboard storage of compressed gaseous fuels. VTO also manages the Energy Efficient Mobility Systems (EEMS) Program, which examines the systemic energy impacts of connected and automated vehicles, where hydrogen and fuel cells can play a potential role in the future, particularly for freight. • The **Renewable Power Offices,** which include the Wind, Solar, Water, and Geothermal Offices, conduct RD&D to enable the integration of renewable power sources with technologies for hydrogen production and utilization, such as integrated wind/electrolysis systems and solar thermochemical systems.	The **Office of Fossil Energy (FE)** 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; carbon capture, utilization, and storage (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 FE programs are currently conducting fossil energy-based hydrogen RD&D: • The **Office of Clean Coal and Carbon Management (CC&CM)** is focused on advancing technologies for producing hydrogen from coal with CCUS, including through modular systems and co-gasification with biomass and waste plastics. Key priorities are hydrogen-combustion turbines and reversible solid-oxide fuel cell systems for large scale power generation as well as integration with gasification islands for large chemical co-production (e.g., ammonia and polygeneration). Reversible solid oxide fuel cell R&D is conducted in coordination with EERE's HFTO to ensure there is no duplication of efforts. FE will also coordinate with EERE, NE, and other offices on hybrid energy systems where reversible SOFCs can be integrated. RD&D emphasis includes combustion and fuel science, catalysis, gasification, separations, as well as CCUS to enable the utilization of carbon-neutral (or even carbon-negative when co-firing biomass) hydrogen at scale. In addition, the office will evaluate the use of hydrogen in energy storage systems and technologies for storing large volumes (>100 tons) on site. Such volumes could be used for emergency supply (when there are fuel supply disruptions at gas turbine facilities such as seen during extreme weather events or other emergencies). 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 Oil and Natural Gas (ONG)** works to increase the energy and economic security of oil and natural gas supplies and typically focuses on early-stage research in natural gas infrastructure and gas hydrates. ONG leverages insight and expertise in oil and natural gas production, transport, storage, and distribution to support RD&D to enable the use of natural gas supply and storage infrastructure and the large-scale delivery and storage (e.g., geological storage) of hydrogen. Focus areas include RD&D to enable the transmission and storage of hydrogen and hydrogen blends in the existing national network of natural gas pipelines and underground reservoirs. Other RD&D areas include: hydrogen-based approaches for mitigating mid-stream emissions from natural gas infrastructure; technologies to convert flared or vented gas to hydrogen products; and technologies to convert natural gas to solid carbon products, hydrogen, and other value-added products. • FE 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)

The **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 concepts. 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:

- Demonstration of both high-temperature and low-temperature electrolysis systems at operating light water reactors that can provide the low-cost heat necessary for these processes 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 concepts and technologies needed to integrate hydrogen production methods with existing and future reactors in ways that optimize the system-level economic, environmental, and safety performance as they operate in concert with other generation sources and end-use technologies.
- 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 partnerships with domestic nuclear industry vendors.
- NE and EERE have collaboratively initiated hydrogen production pilot projects to demonstrate the initial feasibility of such systems at currently operating U. S. nuclear power plants.

Office of Electricity (OE)

The **Office of Electricity (OE)** works with public and private partners to lead DOE's efforts to ensure the nation's most critical energy infrastructure is secure and able to recover rapidly from disruptions. A secure and resilient power grid is vital to national security, economic security, and the services Americans rely upon. OE focuses on four priorities:

1. **The North American Energy Resiliency Model (NAERM)** to enable planning and contingency analysis to address vulnerabilities in the North American energy system.
2. **Megawatt Scale Grid Storage,** working with labs and other DOE offices to integrate new technologies for advancing megawatt scale storage with added resiliency and control capabilities. Focus areas have included flow batteries using aqueous soluble organics, rechargeable Zn-MnO_2 batteries, and sodium-based batteries.
3. **Revolutionize Sensing Technology Utilization,** through development and integration of high-fidelity, low-cost sensing technology for predictive and correlation modeling for electricity.
4. **Transmission,** addressing electricity-related policy issues by carrying out statutory and executive requirements, while also providing policy design and analysis expertise to states, regions, and tribes.

OE collaborates with the Program on hydrogen-related RD&D for power-to-gas applications and long duration energy storage. Other relevant areas of interest include power electronics to enable cost reductions for a range of technologies such as electrolyzers and techno-economic analysis of power-to-gas, which assesses the impacts of RD&D progress, varying grid markets, and regional markets for hydrogen.

Office of Science (SC)

The mission of DOE's **Office of Science (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 (BES)** within the Office of Science supports fundamental research addressing critical challenges related to hydrogen storage, production, utilization, and conversion. These efforts, which include work conducted by the Solar Fuels Hub program and the Energy Frontier Research Centers, complement the technology-specific RD&D supported by other DOE offices and provides 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. Key basic research focus areas 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

Advanced Research Projects Agency-Energy (ARPA-E)

The **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)

As shown in Figures 22 and 23, there is specific inter-office collaboration on a number of technical areas, showing clearly delineated focus areas as well as areas leveraging coordination.

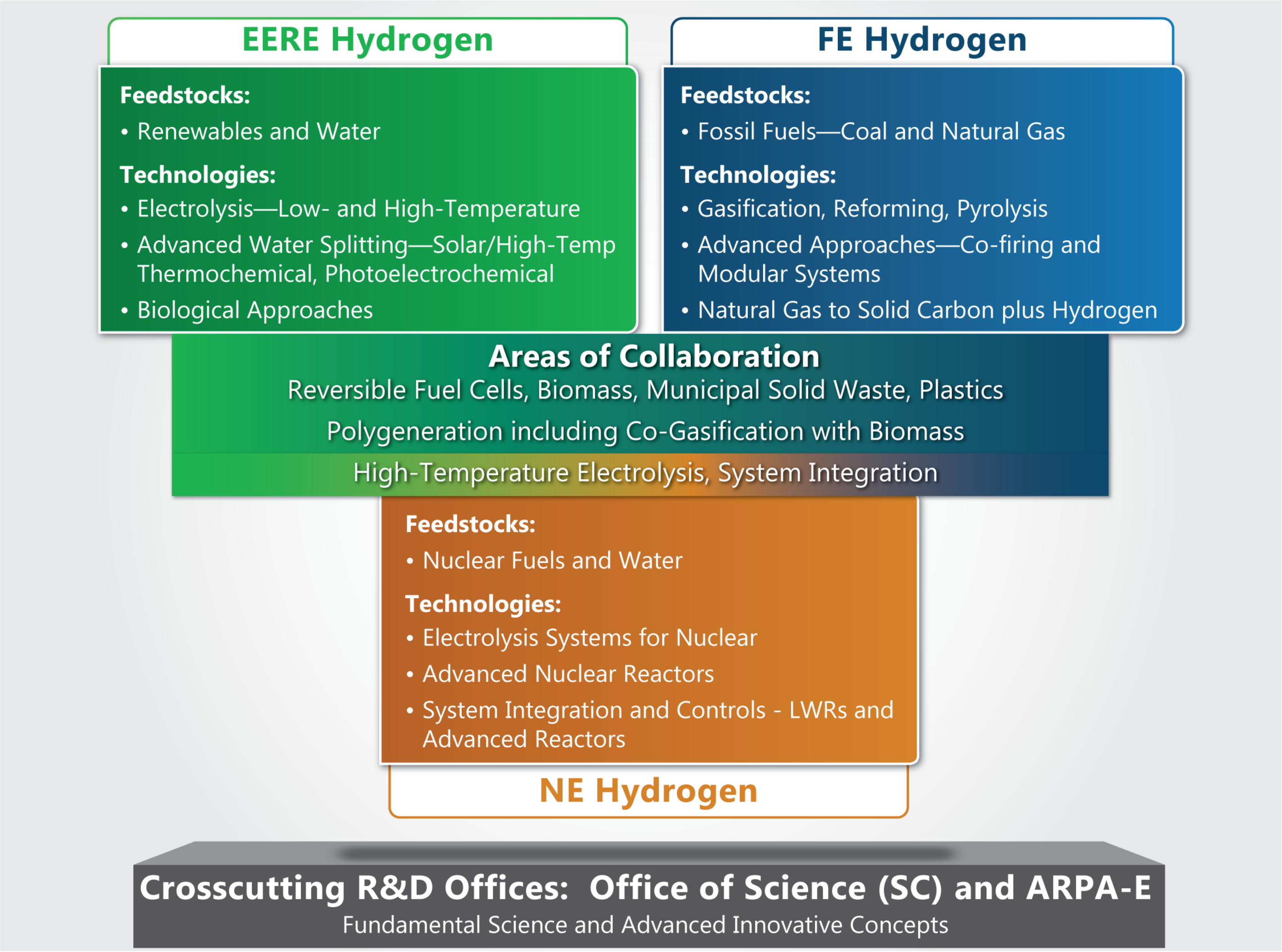

Figure 22. Collaboration on hydrogen production—key focus areas and technologies

FE and NE are primarily focused on large-scale power generation using fossil fuels or nuclear resources, while EERE focuses on renewables as well as 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 AMO). Chemical and fuel production using hydrogen is an area of coordination between EERE and FE, with FE 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.

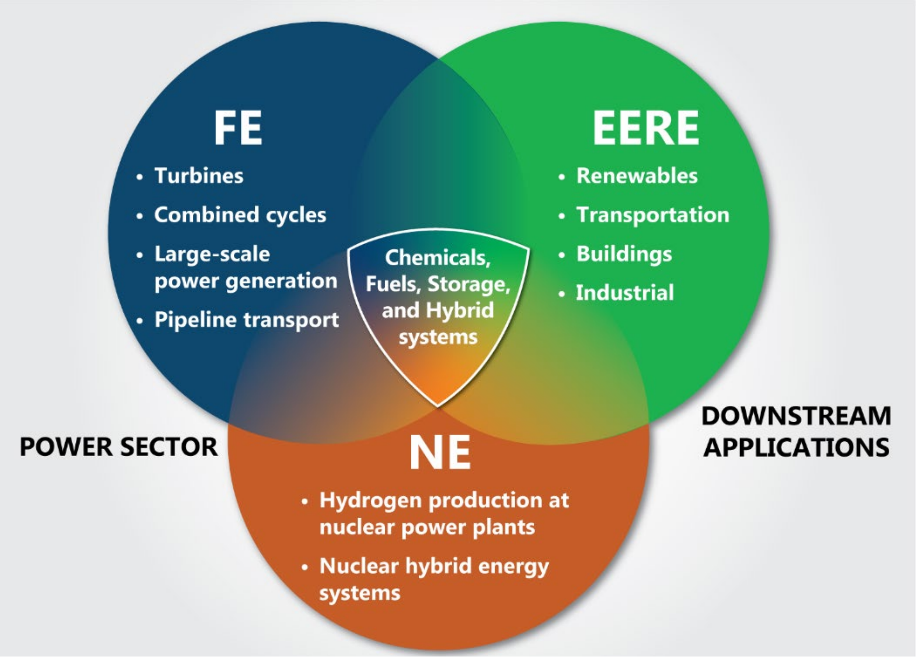

Figure 23. Collaboration on hydrogen applications—key focus areas

Federal and State Coordination

The Program actively pursues opportunities for coordination and collaboration with other federal agencies. By exchanging information on RD&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 (DoD) on early market deployment activities. DoD and DOE have held joint workshops to identify opportunities, challenges, and other areas of common interest.

DOE leads the *Hydrogen and Fuel Cell Interagency Working Group* (IWG),[87] 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. Currently, agencies participating in the IWG include the Department of Agriculture, Department of Commerce, DoD, DOE, Department of Homeland Security, Department of State, Department of Transportation (USDOT), Environmental Protection Agency (EPA), National Aeronautics and Space Administration, National Science Foundation, Office of Science and Technology Policy, and the U.S. Postal Service. DOE, DOT, the EPA, and the National Institute of Standards and Technology (Department of Commerce) also coordinate their activities involving safety, codes and standards, and regulations. For a detailed description of hydrogen-related activities at other federal agencies, see hydrogen.gov, a portal maintained by DOE that provides access to federal efforts related to hydrogen and related technologies.[88] In addition to engagement through the IWG, the Program coordinates directly with the USDOT in a number of areas, including strategic planning and peer reviews with the Volpe National Transportation Systems Center, as well as coordination on issues related to safety, codes and standards with the Pipeline and Hazardous Materials Safety Administration and the National Highway Traffic Safety Administration.

The 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.

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[87] HFTO has led this group for well over a decade, consistent with section 806 of EPACT (2005), 2 U.S.C. §16155, which directs DOE to lead a *Hydrogen and Fuel Cell Interagency Task Force* (ITF).

[88] Hydrogen and Fuel Cells Interagency Working Group. https://www.hydrogen.gov/.

Private Sector and Other Non-Governmental 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 non-profit stakeholders through key partnerships helps to ensure that the RD&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, known as U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), focuses on pre-competitive, 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 VTO, specifically focused on advancing next generation medium- and heavy-duty trucks, including the use of hydrogen fuel cells.[89] 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 (FCHEA), which represents a broad range of stakeholders, including: manufacturers 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 either formally or informally with the Program including: the California Fuel Cell Partnership, the California Hydrogen Business Council, the California Stationary Fuel Cell Collaborative, the Green Hydrogen Coalition, the Colorado Hydrogen Association, the New Jersey Hydrogen Coalition, the Massachusetts Hydrogen Coalition, the Ohio Fuel Cell Coalition, the 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 RD&D areas of interest at a global scale. Key examples include the Clean Energy and Hydrogen Energy Ministerials, the International Energy Agency, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Mission Innovation, the 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 (IEA).** The Program has been active in IEA Technology Collaboration Programs (TCPs), and served as vice chair of the Advanced Fuel Cell (ACF) and Hydrogen TCPs. Created in 1990, the AFC TCP focuses on multiple fuel cell technologies across applications and currently has 16 member countries: Austria, Canada, China, Croatia, Denmark, France, Germany, Israel, Italy, Japan, Korea, Mexico, Spain, Sweden, Switzerland, and the United States.[90] The Hydrogen TCP 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 (EC), and the United Nations Industrial Development Organization (UNIDO). 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.[91]
- **International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE).** Established in 2003, IPHE is an international inter-governmental partnership currently consisting of 20 member-countries and the EC.

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[89] U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy. "21st Century Truck Partnership." Accessed online: https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.

[90] Advanced Fuel Cells. "Who we are." Accessed online: https://www.ieafuelcell.com/index.php?id=8.

[91] International Energy Agency, 2020, op. cit.

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 on safety, regulations, codes, standards, and outreach. IPHE includes working groups on *Regulations, Codes, Standards, and Safety* and on *Education and Outreach*, as well as task forces such as the *Hydrogen Production and Analysis (H2PA)* task force to enable international trade of hydrogen. The Program, through representation from HFTO, is serving 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.

Through incorporating input from international and domestic stakeholders as well as through the in-depth expertise within the 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 chapters. For example, U.S. DOE efforts support the recommendations outlined in the IEA Future of Hydrogen[92] report released at the 2019 G20 Summit:

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 co-operation is essential and supported by a number or 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 corridor; and enabling hydrogen shipping to jumpstart international hydrogen trade.

U.S. DOE activities as outlined in this document are also aligned with the Global Action Agenda[93] as developed through the Hydrogen Energy Ministerial in September 2019. 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 research and development 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"[94]

Figure 24 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

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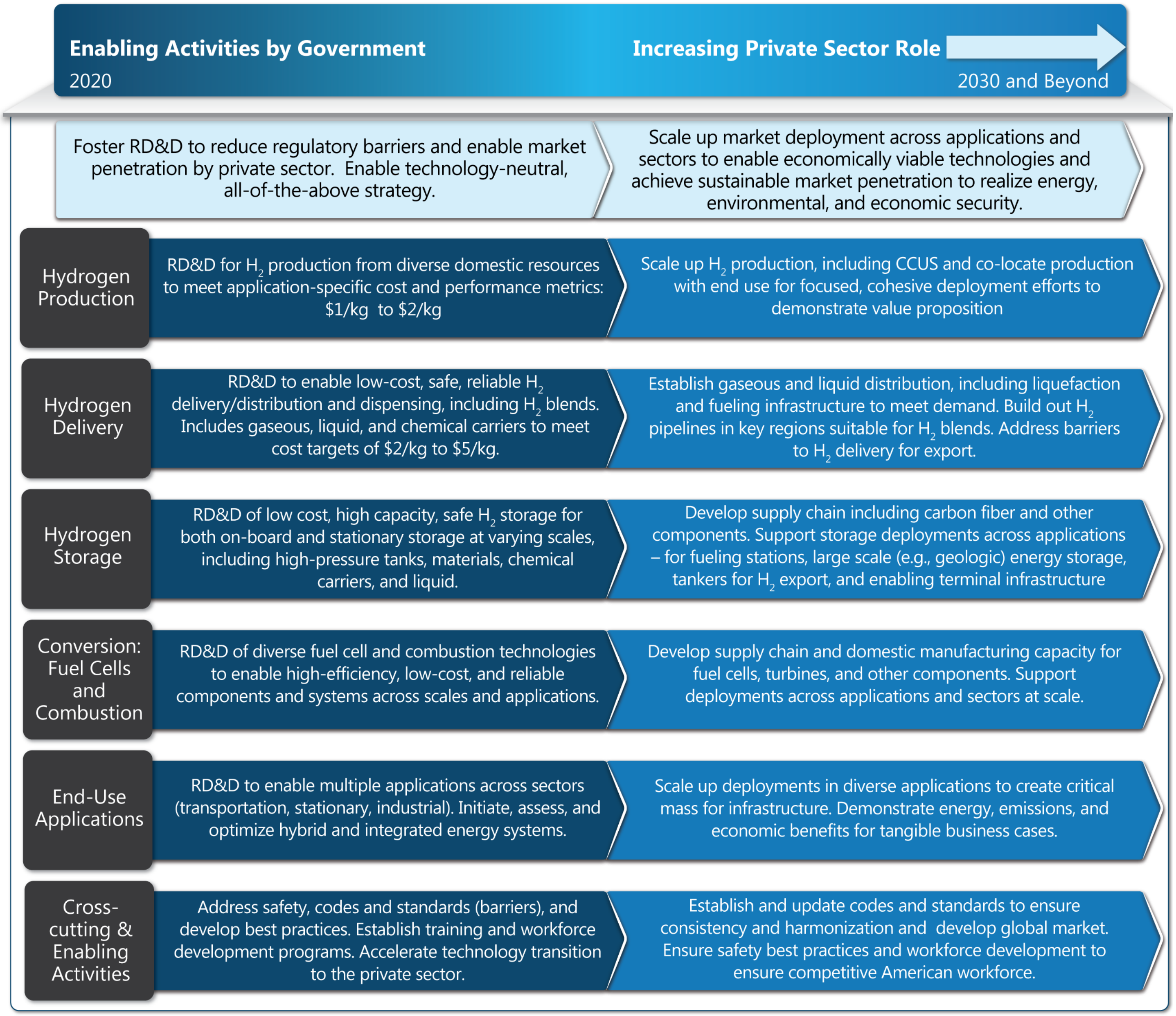
[92] International Energy Agency, 2019, op. cit.

[93] Global Action Agenda. 2019. "Chair's Summary of 2nd Hydrogen Energy Ministerial Meeting – Global Action Agenda of Tokyo Statement." Accessed online: https://www.meti.go.jp/press/2019/09/20190927003/20190927003-5.pdf.

[94] Global Action Agenda.,2019, op. cit.

the international recommendations cited above as well as the *Roadmap to a U.S. Hydrogen Economy*, a document published in 2020 with analysis developed by roughly 20 leading industry stakeholders committed to developing a hydrogen economy in the United States.[95]

Hydrogen Strategy emphasizes Collaborative Activities between Government and Private Sector



	Enabling Activities by Government 2020	**Increasing Private Sector Role** 2030 and Beyond
	Foster RD&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	RD&D for H_2 production from diverse domestic resources to meet application-specific cost and performance metrics: \$1/kg to \$2/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	RD&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	RD&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	RD&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	RD&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 24. DOE Hydrogen Program strategies and enabling activities

In summary, through the cohesive and coordinated efforts by the U.S. Department of Energy'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 Program's vision: A prosperous future for the nation, in which clean hydrogen energy technologies are affordable, widely available and reliable, and are an integral part of multiple sectors of the economy across the country.

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[95] UShydrogenstudy.org, 2019, op. cit.

Appendix A: Domestic energy resources required to produce 10 million metric tonnes (MMT) of hydrogen

A key aspect of the Department'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, etc.) 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 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 are based on the National Renewable Energy Laboratory's update to a 2013 analysis, and they incorporate input from peer-reviews by multiple DOE offices as well as input from external stakeholders.[96]

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[96] Connelly, et al., 2020, op. cit.

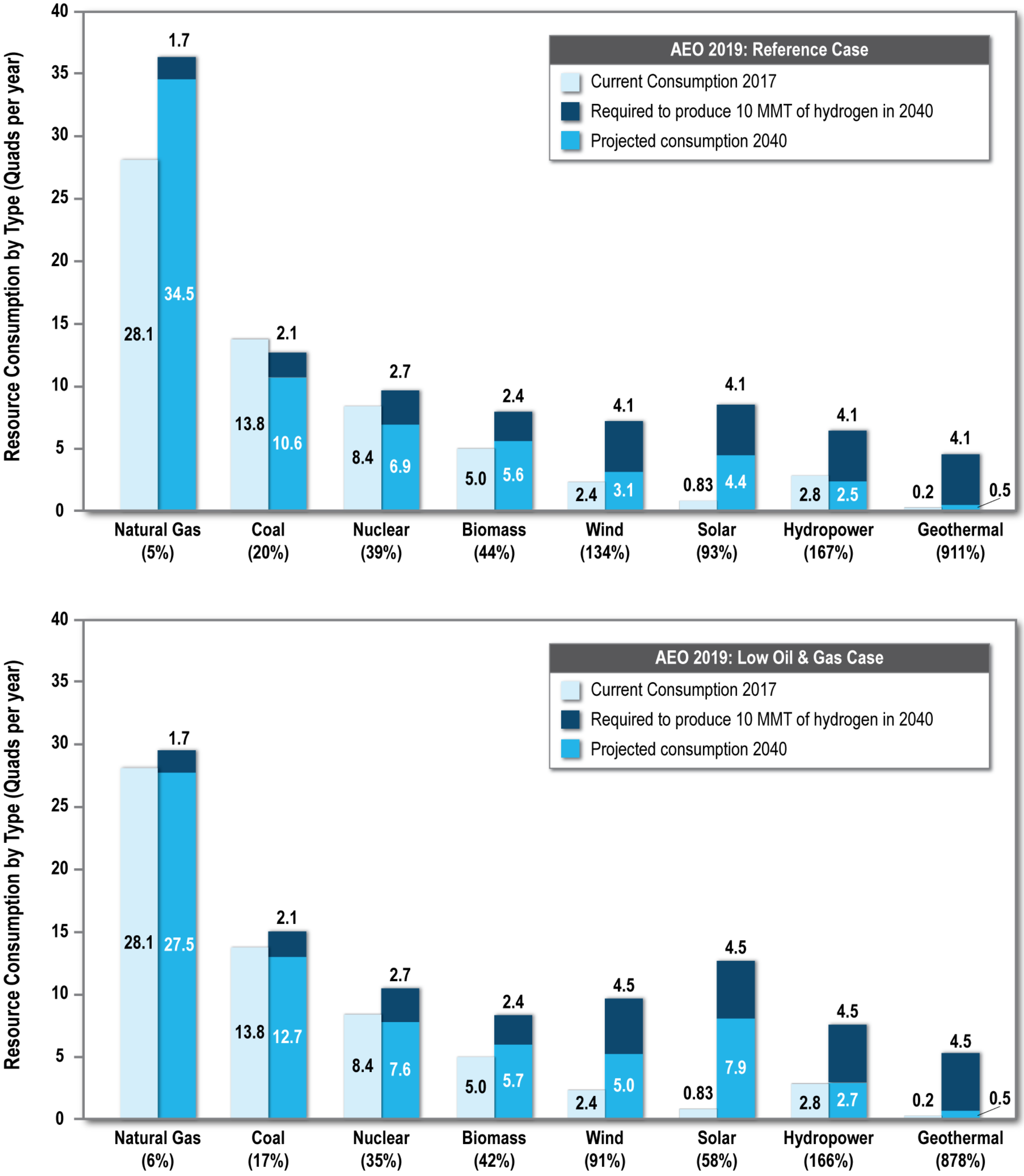

Figure A-1. The amount of each energy resource that would be required to produce 10 MMT/yr hydrogen (using each resource on its own), relative to current (2017) and projected (2040) energy consumption in the Annual Energy Outlook's Reference Case (top) and Low Oil and Gas Case (bottom).

The light blue bars indicate current (2017) consumption of each resource, the medium blue bars represent projected (2040) consumption, and the dark blue bars depict the amount of additional resource that would be necessary to produce 10 MMT/yr 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.

Appendix B: Glossary of Acronyms

ADG	anaerobic digester gas
AMO	Advanced Manufacturing Office
ARPA-E	Advanced Research Program Agency-Energy
ATR	autothermal reforming
BES	Office of Basic Energy Sciences
BETO	Bioenergy Technologies Office
BOP	Balance-of-plant
BTU	British thermal unit
CC&CM	Office of Clean Coal and Carbon Management
CCUS	carbon capture, utilization, and storage
CHP	combined heat and power
CRADA	Cooperative Research and Development Agreement
DAYS	Duration Addition to Electricity Storage
DoD	Department of Defense
DOE	Department of Energy
DRI	direct reduction of iron
EC	European Commission
EERE	Office of Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
EPACT	Energy Policy Act of 2005
ESGC	Energy Storage Grand Challenge
FCEV	fuel cell electric vehicle
FCHEA	Fuel Cell and Hydrogen Energy Association
FE	Office of Fossil Energy
FOA	funding opportunity announcement
g/l	grams per liter
GW	gigawatt
H_2	hydrogen
H2PA	Hydrogen Production and Analysis
HDV	heavy-duty vehicle
HES	hybrid energy system
HFI	Hydrogen Fuel Initiative
HFTO	Hydrogen and Fuel Cell Technologies Office
IEA	International Energy Agency
INTEGRATE	Innovative Natural-Gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-Generation
IONICS	Integration and Optimization of Novel Ion-Conducting Solids
IMO	International Maritime Organization
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
ITF	Hydrogen and Fuel Cell Interagency Task Force
IWG	Hydrogen and Fuel Cell Interagency Working Group

Kg	kilogram
kWh/l	kilowatt hour per liter
LDV	light-duty vehicle
LPO	Loan Program Office
MDV	medium-duty vehicle
MMT	million metric tonnes
MOF	metal-organic framework
MT	metric tonne (1,000 kg)
MW	megawatt
NAERM	North American Energy Resiliency Model
NIST	National Institute of Standards and Technology
NE	Office of Nuclear Energy
NGLs	natural gas liquids
NH_3	ammonia
OE	Office of Electricity
ONG	Office of Oil and Natural Gas
OTT	Office of Technology Transitions
PEC	photo-electrochemical water splitting
PEMFC	polymer electrolyte membrane fuel cell
PPM	parts per million
PSI	pounds per square inch
REBELS	Reliable Electricity Based on Electrochemical Systems
REEACH	Range Extenders for Electric Aviation with Low Carbon and High Efficiency
REFUEL	Renewable Energy to Fuels through Utilization of Energy-dense Liquids
R&D	research and development
RD&D	research, development, and demonstration
RFI	Request for Information
SC	Office of Science
SMR	steam methane reforming
SOFC	solid oxide fuel cell
SPP	Strategic Partnership Project
STCH	solar thermochemical hydrogen
TCP	Technology Collaboration Program
U.S. DRIVE	Driving Research and Innovation for Vehicle efficiency and Energy sustainability
USDOT	U.S. Department of Transportation
UNIDO	United Nations Industrial Development Organization
VTO	Vehicle Technologies Office
WFO	work for others

Appendix C: Contacts & Links

DOE Hydrogen Program Contacts

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Links to Relevant Organizations

DOE Hydrogen Program: www.hydrogen.energy.gov

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

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

DOE Office of Fossil Energy: https://www.energy.gov/fe/office-fossil-energy

- Office of Clean Coal and Carbon Management: https://www.energy.gov/fe/science-innovation/office-clean-coal-and-carbon-management
- Office of Oil and Natural Gas: https://www.energy.gov/fe/science-innovation/oil-gas-research
- Solid Oxide Fuel Cell Program: https://www.energy.gov/fe/science-innovation/clean-coal-research/solid-oxide-fuel-cells

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

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

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

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

Advanced Research Projects Agency-Energy (ARPA-E): https://arpa-e.energy.gov/

Hydrogen and Fuel Cells Interagency Working Group: https://hydrogen.gov/

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