U.S. DEPARTMENT OF
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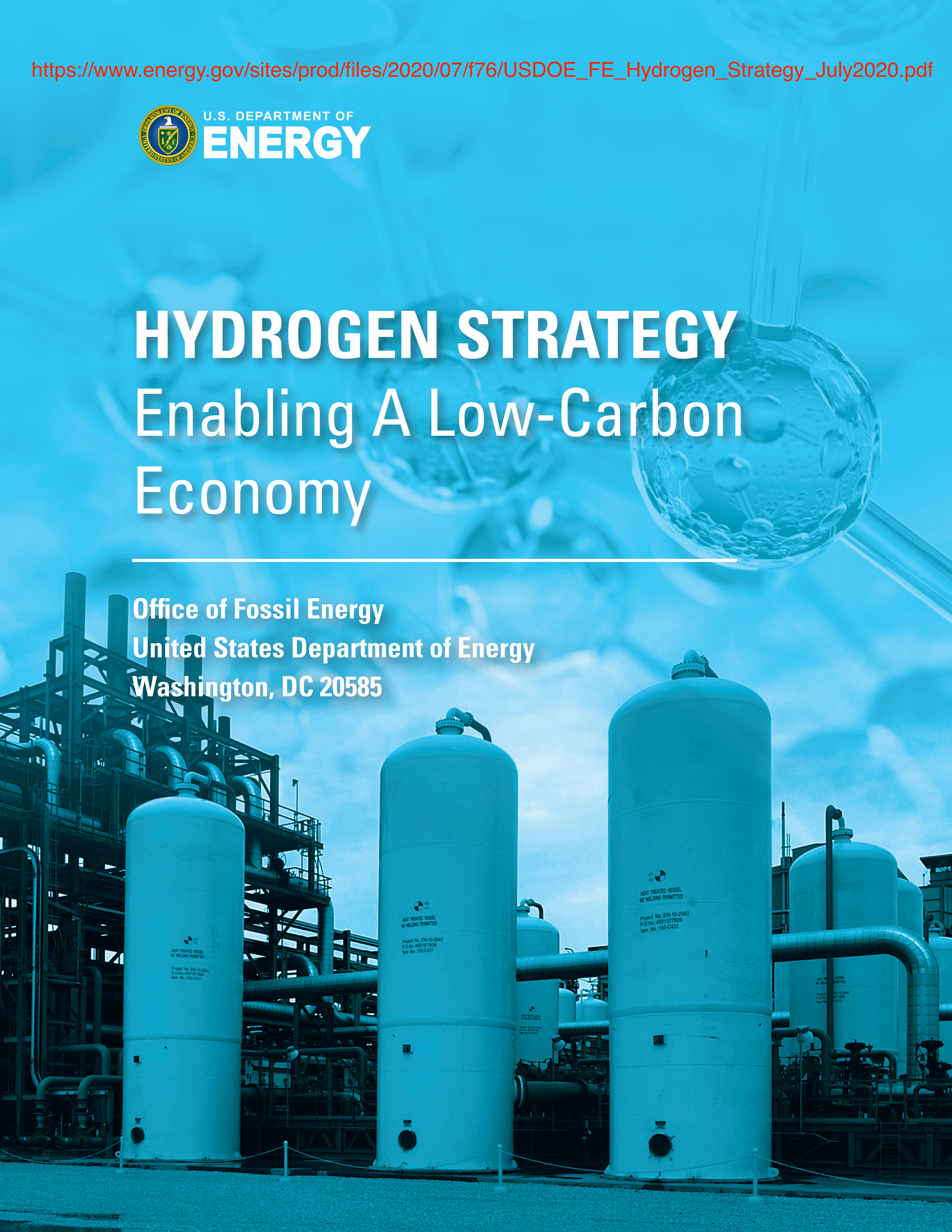

HYDROGEN STRATEGY
Enabling A Low-Carbon Economy

Office of Fossil Energy
United States Department of Energy
Washington, DC 20585

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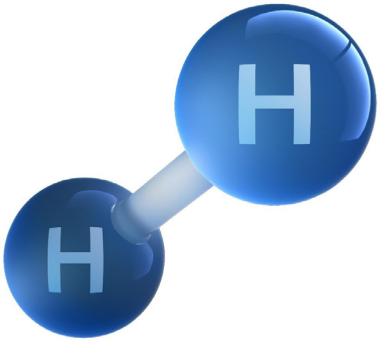

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Introduction

This document summarizes current hydrogen technologies and communicates the U.S. Department of Energy (DOE), Office of Fossil Energy's (FE's) strategic plan to accelerate research, development, and deployment of hydrogen technologies in the United States. It also describes ongoing FE hydrogen-related research and development (R&D). Hydrogen produced from fossil fuels is a versatile energy carrier and can play an important role in a transition to a low-carbon economy.

Hydrogen (H_2) is the simplest and most abundant element in the universe, and it only occurs naturally on Earth when combined with other elements. Hydrogen, like electricity, is an energy carrier (fuel) that can be used to store, move, and deliver energy produced from other sources. It can be produced without a carbon footprint from a variety of sources, including natural gas, coal, biomass, waste materials (i.e., plastics), or splitting water molecules. Gasification of fossil fuels with biomass and plastics is expected to be the lowest-cost route to providing carbon negative hydrogen when using carbon capture, utilization, and storage (CCUS) technologies.

Scientists have been interested in hydrogen as a source of energy since the 1800s,[1] and it is currently an essential feedstock and fuel in many industries. Primary uses of hydrogen include the following applications: (1) as a chemical in ammonia (NH_3) production (mainly for fertilizers), (2) as a chemical feedstock and catalyst, (3) as a hydrogenating agent for food and drug production, and (4) in petrochemical and refinery processing. Hydrogen consumed by large volume users is typically generated onsite (captive hydrogen), and for industries such as glass manufacture, food, and electronics, it is supplied by trailers (merchant hydrogen).

In addition, hydrogen is emerging as a low-carbon fuel option for transportation, electricity generation, and manufacturing applications, because it could decarbonize these three large sectors of the economy. Hydrogen has the highest energy content of any common fuel per unit of weight, but it is less dense than other fuels, which hinders its wide-scale deployment. While hydrogen fuel consumption is not widespread, there has been growing interest in its use as a potential fuel source across the economy. In fact, its use is projected to significantly increase in many countries through 2050 as these countries transition toward a low-carbon economy.[2]

According to the International Energy Agency (IEA) report, *Energy Technology Perspectives 2017*,[3] by 2050, fossil fuels will remain the primary source of hydrogen for the United States (~75%), Europe (~65%), and Japan (~85%). This forecast is based on the regional abundance of fossil fuels, the low cost of hydrogen production, and other benefits (e.g., reduced emissions) of sourcing hydrogen from fossil fuels with CCUS, rather than using it for power generation directly.

As the lead Federal agency for energy R&D, DOE develops technologies to diversify and increase domestic energy supplies and make energy more affordable, improve domestic energy production and use, and enhance the security, reliability, and resilience of energy infrastructure. FE has a broad portfolio of R&D activities and is focused on technological advancements that could enable a transition toward a low-carbon economy with hydrogen. DOE is well positioned to accelerate this transition by developing technology solutions that enable the production of hydrogen from fossil fuels with neutral, or even negative, carbon emissions. FE's depth of experience and R&D conducted over the past 30 years have been focused on fossil fuels. Future efforts can be summarized in four major R&D focus areas:

1. Carbon-Neutral Hydrogen Production Using Gasification and Reforming Technologies
2. Large-Scale Hydrogen Transport Infrastructure
3. Large-Scale Onsite and Geological Hydrogen Storage
4. Hydrogen Use for Electricity Generation, Fuels, and Manufacturing.

Beyond R&D, FE can also leverage past experience in hydrogen handling and licensing reviews for liquefied natural gas (LNG) export to support U.S. hydrogen export. For example, FE is well positioned to help develop safety and other requirements for hydrogen export facilities, which will be essential to materializing U.S. exports to global markets that are shifting to greater hydrogen use in electricity, manufacturing, transportation, or residential sectors.

Background

While DOE has an overarching Hydrogen Program Plan, this document focuses on the Office of Fossil Energy R&D efforts. DOE's Office of Energy Efficiency and Renewable Energy (EERE) and Office of Nuclear Energy (NE) are also actively pursuing R&D in different areas and technologies for hydrogen production, transport, delivery, and storage.

The H2@Scale program has developed an illustration to represent the hydrogen activities of the Department and it has been modified in the shaded areas for the purpose of better illustrating how the FE R&D will support the low-carbon hydrogen economy (see Figure 1).

For the past 20 years, FE—in partnership with industry—has pioneered the direct use of hydrogen for power generation. The office's sponsored research has resulted in the development of hydrogen combustion turbines for power generation and combustors that can replace the natural gas combustors in commercially available combustion turbines. Research is currently underway on technologies that can produce hydrogen from coal-derived synthesis gas and build and operate a zero-emissions, high-efficiency energy plant that coproduces hydrogen and electricity from coal, biomass, and waste. Efforts to enable 100% hydrogen firing in utility-scale combustion turbines are also in progress.

FE and industry have the potential to leverage ongoing work and existing infrastructure to improve the economics of hydrogen production from natural gas via steam methane reforming (SMR) process[a] and coal/biomass/waste plastic gasification with CCUS to realize negative carbon dioxide (CO_2) emissions. In addition, there is growing interest in conversion of natural gas to hydrogen and solid carbon, thereby providing an additional byproduct revenue stream. Such innovations in the use of our abundant natural gas resources have the potential to strengthen existing and future markets.

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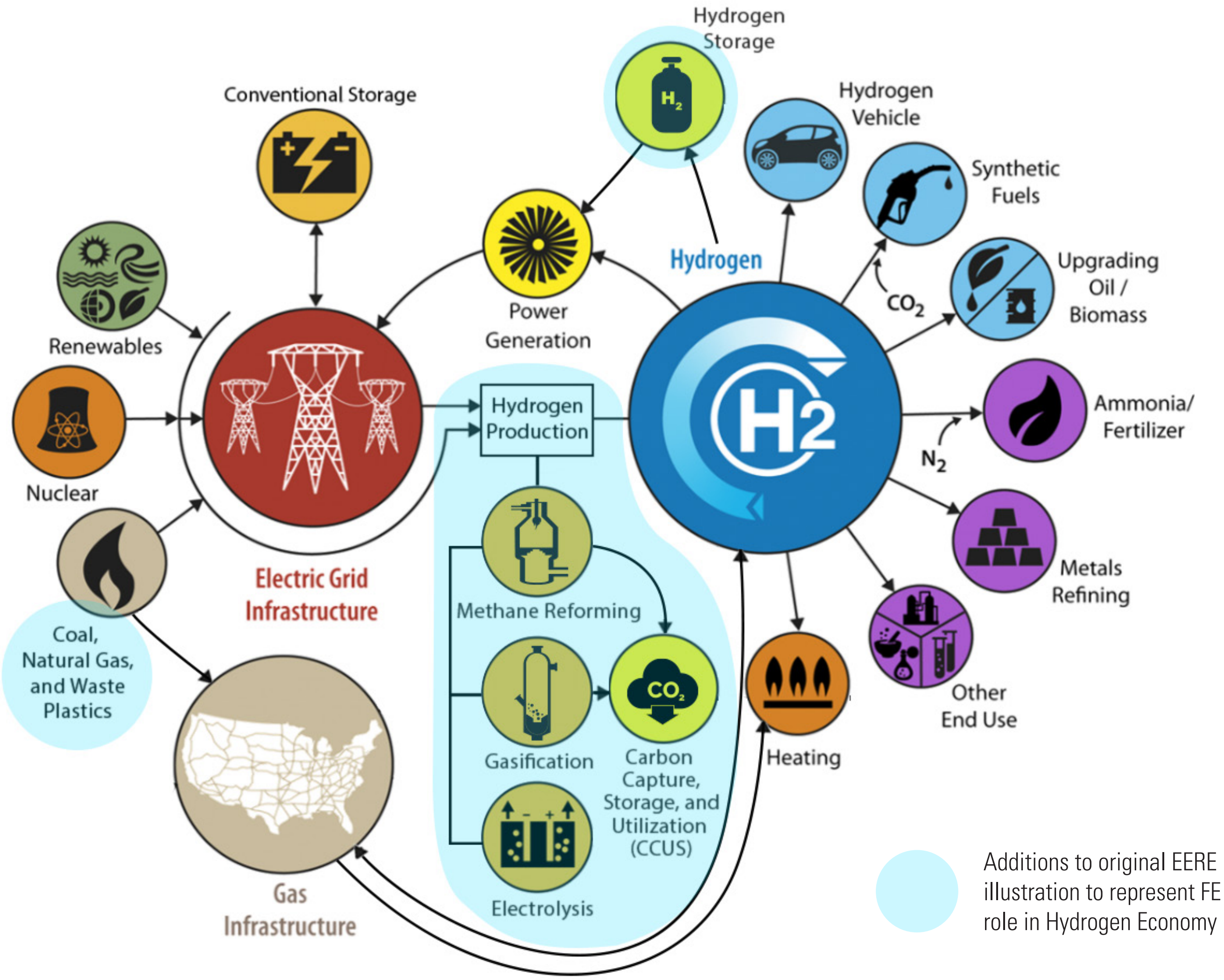
[a] SMR involves the reaction of natural gas and steam over a nickel-based catalyst. This breaks the methane component of the natural gas into carbon monoxide (CO) and H_2 gas, similar to synthesis gas (syngas) produced via gasification. Then water-gas shift (WGS) reaction is performed to increase the amount of H_2 in the product gas as much as possible.

Figure 1. Integration of Fossil Energy into the Hydrogen Economy[4]



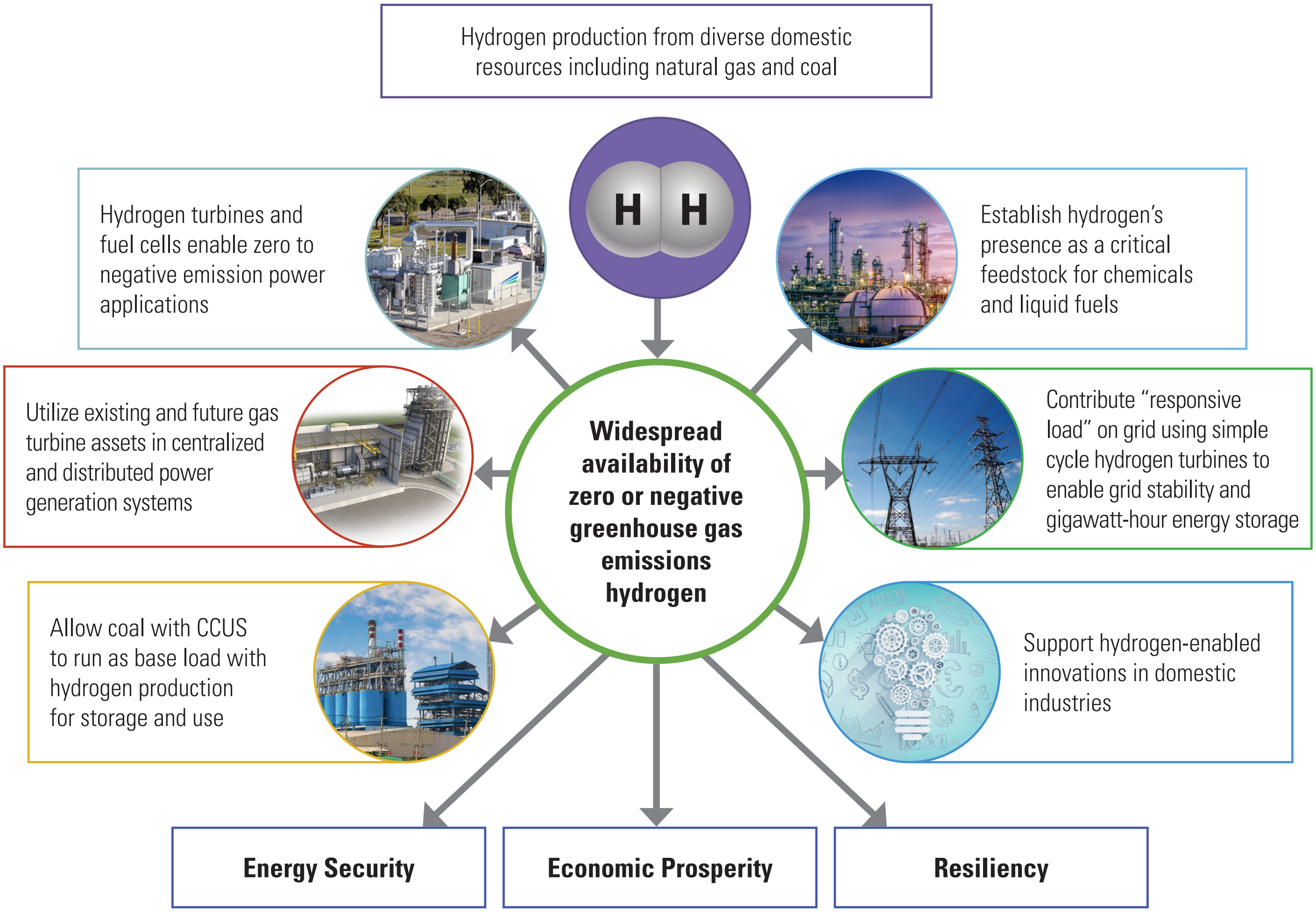
U.S. energy security, resiliency, and economic prosperity are enhanced through:

- Producing hydrogen from diverse domestic resources, including coal, biomass, natural gas, petroleum, petroleum products (e.g., waste plastics), and other recyclable materials with CCUS
- Gasifying blends of coal, biomass, waste plastics, and other recyclable materials with CCUS results in hydrogen produced with net-negative carbon emissions and other environmental benefits when CCUS is integrated with the gasifier
- Having hydrogen widely available for the chemicals and liquid fuels industries
- Using carbon-neutral hydrogen in transportation, stationary or remote power, and portable power applications using hydrogen turbines and fuel cell technologies
- Utilizing gas turbine assets for on-demand centralized and distributed power generation with near-zero emissions
- Supporting reliability and resiliency on the grid using simple-cycle or combined-cycle hydrogen turbines to enable grid stability and large-scale (e.g., gigawatt-hour) energy storage

- Increasing hydrogen storage and power generation supports intermittent renewable power generators where bulk electricity storage is not adequate to cover demand
- Providing large-scale energy storage capacity using hydrogen for both transportation and generation needs without the need to process and consume vast quantities of critical minerals required by electricity storage technologies (e.g., batteries)
- Allowing technologies like coal with CCUS and nuclear power to run in a steady-state mode and producing hydrogen for storage and use when the demand for electricity is low
- Supporting hydrogen-enabled innovations in domestic industries, thereby promoting manufacturing of advanced products.

Figure 2 provides an overview of hydrogen uses and national benefits and shows the relationship of FE's R&D program elements to support a hydrogen economy in the United States.

Figure 2. Relationship of FE Program Elements to Comprehensive Hydrogen Strategy

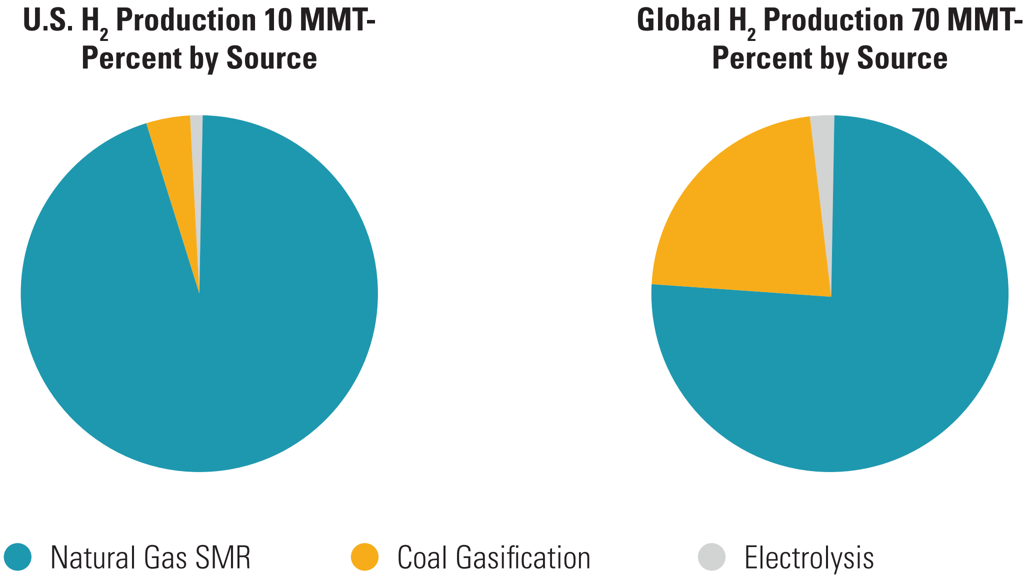


Hydrogen Production and Cost

Currently, 99% of U.S. hydrogen production is sourced from fossil fuels, with 95% from natural gas by SMR and 4% by partial oxidation of natural gas via coal gasification. Only 1% of U.S. hydrogen is produced from electrolysis.[b] Annually, the United States produces more than 10 million metric tons (MMT) of hydrogen, and approximately 60% of it is produced in "dedicated" hydrogen production facilities as their primary product.

Global hydrogen production is approximately 70 MMT, with 76% produced from natural gas via SMR, 22% through coal gasification (primarily in China), and 2% using electrolysis (see Figure 3).

Figure 3. U.S. and Global Production of Hydrogen



SMR is a mature production process that builds upon the existing natural gas pipeline delivery infrastructure. Another well-developed, but more expensive approach for hydrogen production is splitting water. Methods used include electrolysis, photo-electrochemical cells, or solar thermochemical systems. Globally, supplying hydrogen to industrial users is a major business, and the demand has grown more than threefold since 1975, and it continues to rise.[5] Industrial technologies for hydrogen production include catalytic steam reforming (800–1000°C) and partial oxidation (600–900°C) of hydrocarbons (e.g., natural gas) or renewable fuels (e.g., bioethanol); coal or coal blends with biomass and waste plastics gasification; water electrolysis; thermochemical water splitting at around 900°C; and biological production.

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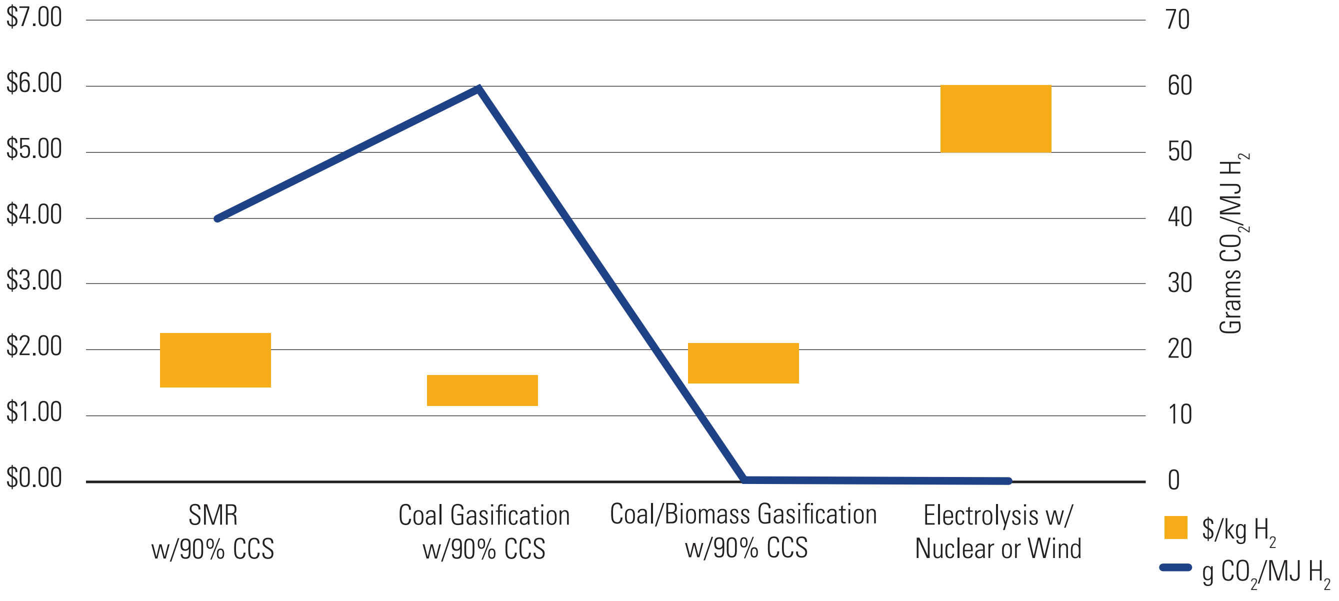
[b] Water electrolysis is the electrochemical splitting of water into hydrogen and oxygen.

Given the substantial economic advantage of gasification and methane reforming with CCUS, in all likelihood, they will be the lowest cost source of large-scale hydrogen for the foreseeable future. As shown in Figure 4, hydrogen production from fossil fuels is the least expensive source of hydrogen. Steam reforming of natural gas for hydrogen production costs vary from $1.43/kg to $2.27/kg with CO_2 capture and storage (CCS) and are highly dependent on the delivered natural gas price. Numerous studies report the cost of hydrogen from gasification to vary between $1.16/kg and $1.63/kg for coal and between $1.31/kg and $2.06/kg for coal/biomass/waste plastic with CO_2 capture and storage. These processes are also highly dependent on the delivered feedstock price. Hydrogen production cost through electrolysis at a centralized station is estimated at $5/kg to $6/kg with electricity from nuclear or wind resources. Hydrogen from zero-carbon electricity, such as nuclear or wind, is 2.5–4 times more costly than hydrogen from carbon-neutral or net-negative carbon fossil resources.

The cost of hydrogen production varies between regions, with Europe and Japan having relatively high costs and strong policy support for hydrogen. Hydrogen importers stand to benefit from cheaper, low-carbon energy—especially if their domestic renewable energy, nuclear, or CCUS resources are challenging or expensive to develop. According to the IEA, in the future, it may be cheaper in some instances for some countries to import hydrogen than to produce it domestically.

Figure 4. Current Cost of Hydrogen Production and CO_2 Intensity

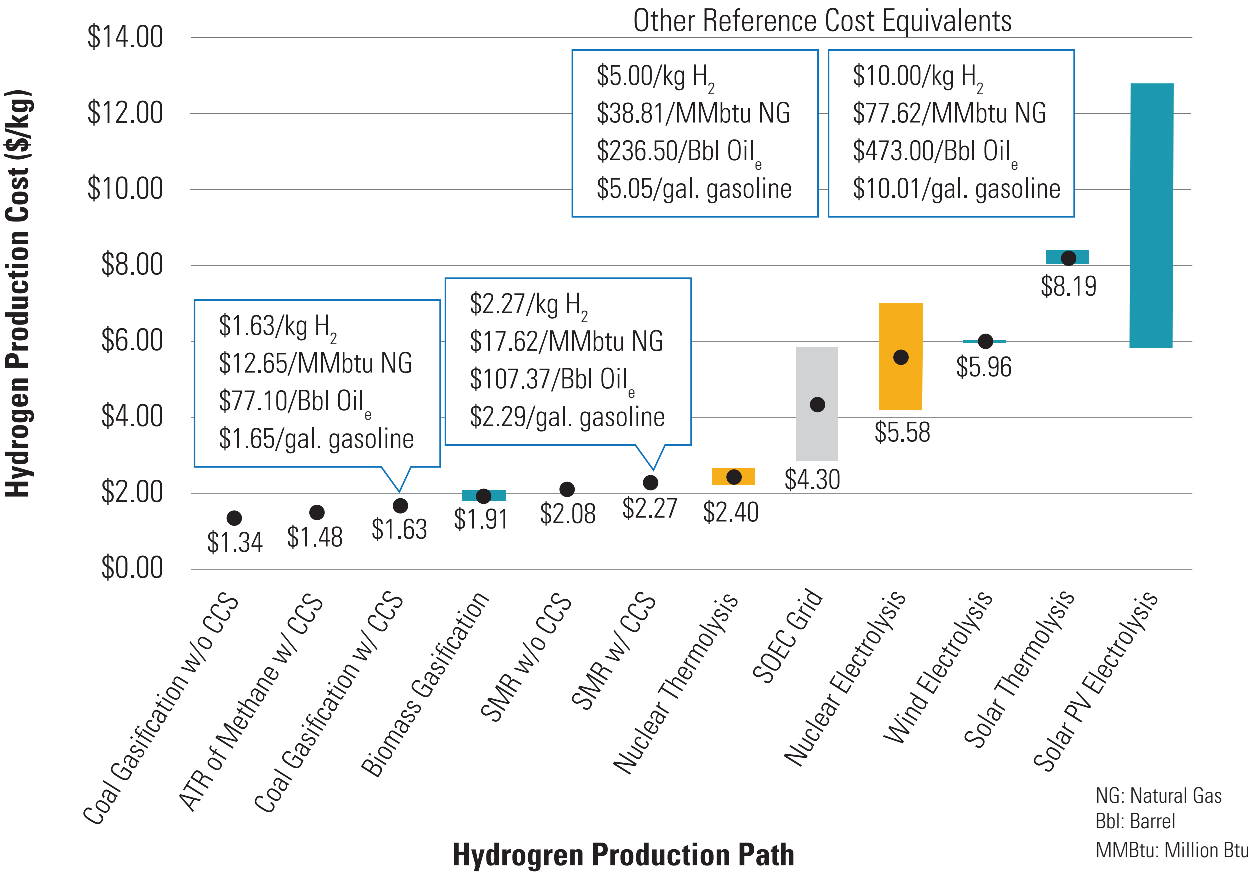


(Source: IEA Roadmap for Hydrogen and Fuel Cell and DOE Baseline Studies)

Hydrogen Uses and Equivalent Costs

Primary uses of hydrogen today are as a chemical feedstock in ammonia, food, and drug production, as well as petrochemical and refinery processing. It is also used in crystal growth, glass manufacturing, chemical tracing, metal fabrication, polysilicon and semiconductor manufacturing, metal production, and thermal processing. Hydrogen from fossil energy could be an economically competitive, carbon-neutral alternative to traditional fuels used in the electricity, industrial, and transportation sectors. Figure 5 below provides a compilation of current hydrogen production costs and supports the Office of Fossil Energy plans to continue investments in Hydrogen related R&D. Costs for hydrogen production from other sources, such as the DOE applied program offices, DOE Office of Science sponsored research group, IEA, many universities, and industry have published figures similar, and in some instance lower than the ones represented below.[6, 7, 8, 9, 10]

Figure 5. Current Hydrogen Production Cost Ranges and Averages by Technology and Equivalent Prices for Fossil Sources with CO_2 Capture and Storage



Oil refinery hydrogen demand is a major component of the overall hydrogen production. Hydrogen is used to remove sulfur and to hydrotreat and hydrocrack heavier crude oil constituents into more valuable, lighter products.[11] In turn, growth in refinery hydrogen demand is affected by an increase in demand for liquid fuels, changes in sulfur content of the raw crude oil, and regulations that limit the amount of sulfur in the liquid fuel. Fertilizer and chemical production also consume large quantities of hydrogen. The U.S. ammonia supply is dependent on the price of natural gas and the supply has increased because of the low price of natural gas. Both brownfield capacity expansions and greenfield ammonia plants are coming online, leading to increased demand for hydrogen.[12]

Other potential hydrogen utilization areas include the following:[13]

- **Industrial Uses**: Hydrogen can replace coke and natural gas as a reducing agent in iron and steel production. Similarly, hydrogen can enable decarbonization of industries, such as cement, fertilizer, and petrochemicals. However, in some cases, considerable R&D may be required to assess the effects of switching from natural gas or coal-derived fuel gases to pure hydrogen.
- **Transportation**: Hydrogen-powered fuel cell vehicles offer both high efficiency and low emissions. They can play an increasingly important role in reducing emissions from long-haul trucks, heavy-duty trucks, buses, medium and large cars, vans, minibuses, trains, ships, and planes.
- **Power Generation**: Hydrogen use for power generation is negligible today, though there is potential for its role in power production. Hydrogen can be injected into existing natural gas pipeline networks or directly sent into the end-distribution network. Hydrogen-fired gas turbines and combined-cycle gas turbines could also be a source of flexibility in electricity systems. In addition, Solid Oxide Fuel Cells (SOFCs) can offer the highest conversion efficiency of chemical-energy-to-electrical-energy of any energy conversion technology, compared to any heat engine.
- **Energy Storage/Grid Balancing**: Hydrogen could become a long-term storage option to balance seasonal variations in electricity demand. Industry has been working on technologies to store hydrogen in cryogenic vessels or in high-capacity sorbents to increase the energy density and duration available. Geologic storage of hydrogen is feasible in salt caverns and other formations. A limited number of geologic storage projects exist in the United States, which could expand as the demand for hydrogen increases.

Hydrogen Demand

According to the IEA report, *Future of Hydrogen*, demand for hydrogen in its pure form will be around 73 million tonnes per year (Mt/year), as shown in Figure 6.[14] One-third of global supply is “by-product” hydrogen, meaning that it comes from facilities and processes designed to manufacture other products. Today’s hydrogen industry is large, with many sources and uses. In energy terms, total annual hydrogen demand worldwide is around 330 million tonnes of oil equivalent (Mtoe), which is larger than the primary energy supply of Germany.[15]

Figure 7 shows an overview of the demand for hydrogen from selected U.S. industries. The quantity of onsite (captive) and merchant hydrogen supplied varies by industry. For example, hydrogen used in oil refining is split almost evenly between captive production and merchant hydrogen suppliers. On the other hand, hydrogen for glass manufacture is almost entirely supplied by merchant suppliers. Merchant producers can supply hydrogen as a liquid or gaseous product, or via a pipeline. Smaller quantities of gaseous, high-pressure hydrogen (to be transported over relatively small distances) are sold in tube trailers.[16]

Figure 6. Worldwide Hydrogen Value Chains

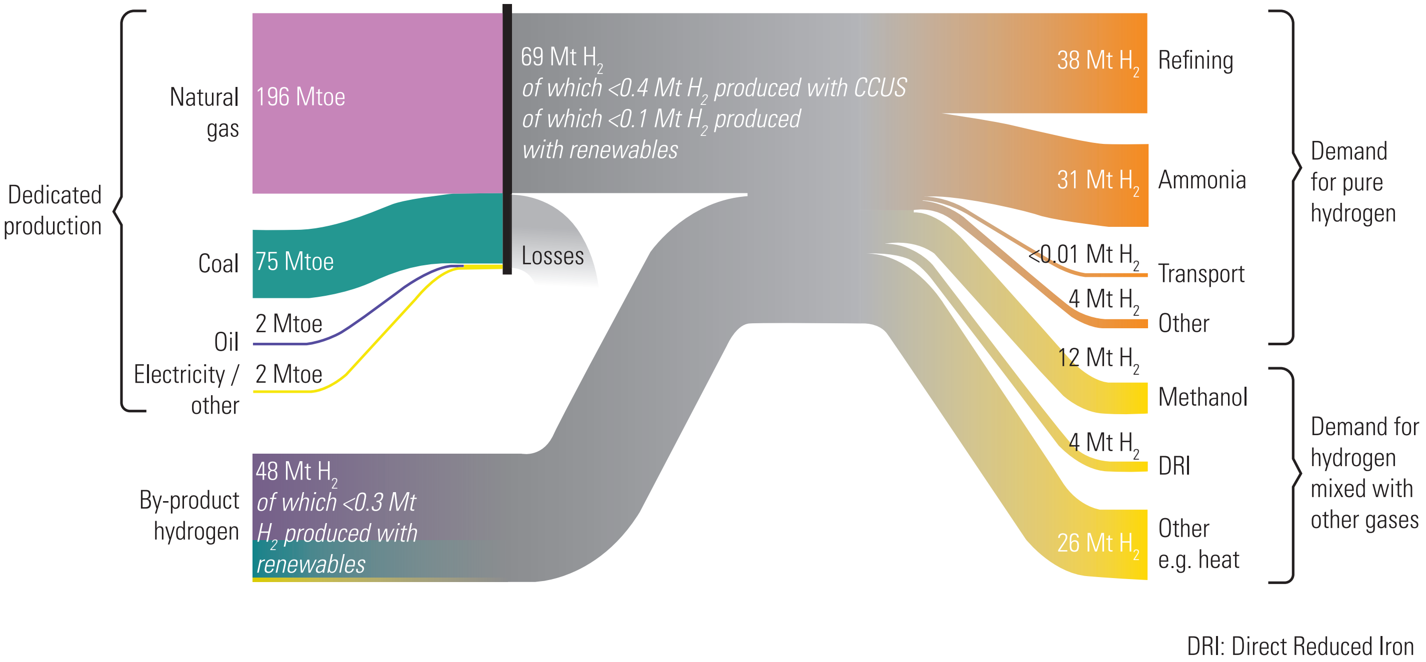
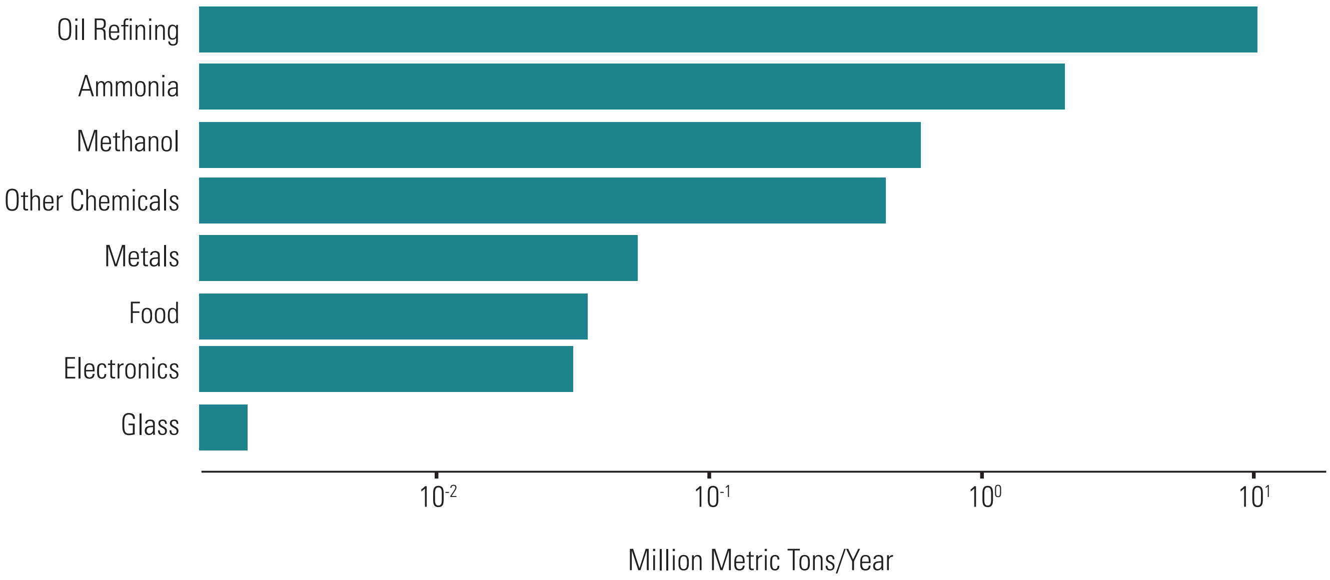


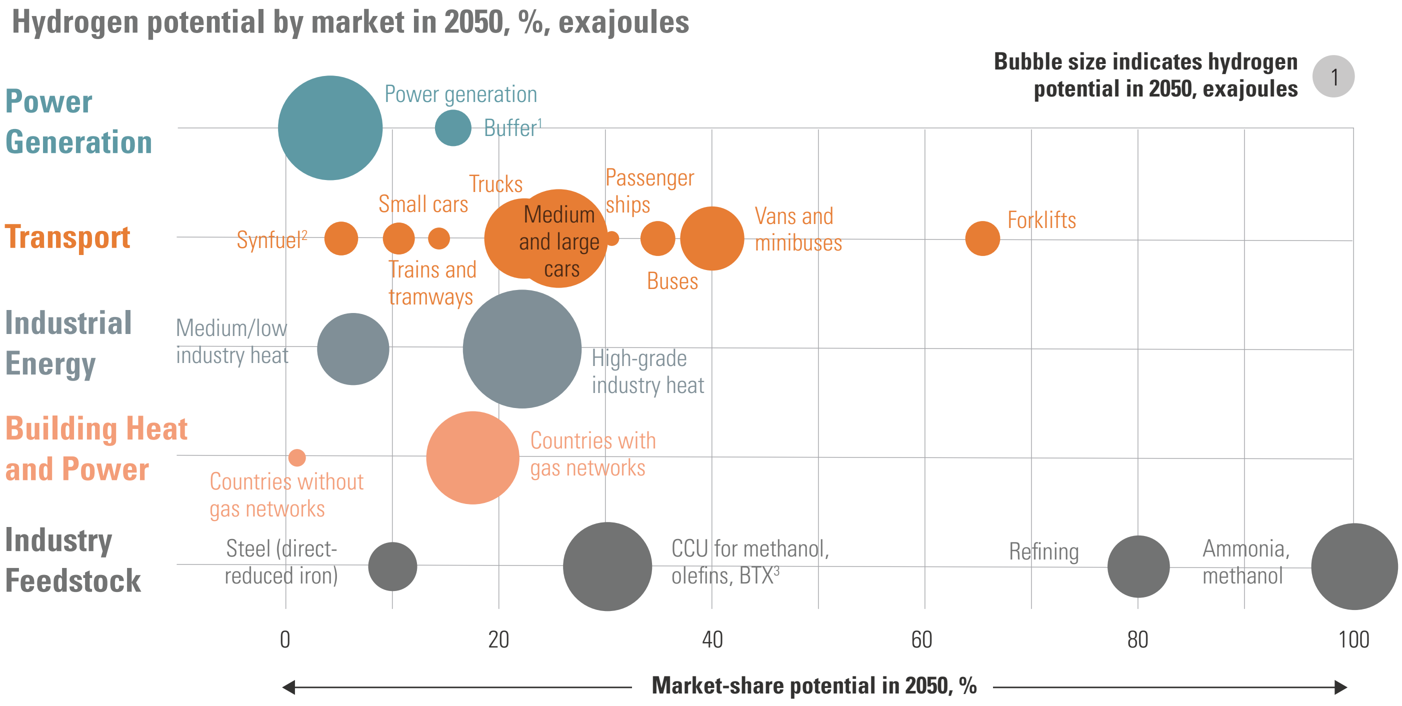
Figure 7. U.S. Hydrogen Demand by Industry Sectors in 2015[17]



Emerging Markets and International Initiatives

Hydrogen holds long-term promise in many sectors beyond existing industrial applications. The transportation, construction, and power sectors all have the potential to use hydrogen if the costs of production and utilization prove this fuel to be competitive compared to other options. Figure 8 shows the global potential for future use of hydrogen and the market share by 2050.[18, 19]

Figure 8. Global Potential for Future Use of Hydrogen



[1] % of total annual growth in hydrogen and variable renewable-power demand.

[2] For aviation and freight ships.

[3] Carbon capture and utilization; % of total methanol, olefin, and benzene, toluene, and xylene (BTX) production using olefins and captured carbon.

IEA's *Future of Hydrogen* report also found that globally, clean hydrogen is experiencing unprecedented political and business momentum, with the number of policy initiatives and projects expanding rapidly.[20] The report concludes that there is a window of opportunity to scale up technologies and reduce costs to allow broad usage of hydrogen. To take full advantage of this momentum, IEA made recommendations to governments and industry focused on two key areas:

1. **Hydrogen can help tackle critical energy challenges**. It offers ways to decarbonize a range of sectors, including long-haul transport, chemicals, iron, and steel industries, and to utilize existing gas turbine assets, where it is proving difficult to meaningfully reduce emissions. It can also help improve air quality and strengthen energy security.
2. **Hydrogen is versatile**. Technologies already available today enable hydrogen to produce, store, move, and use energy in different ways. Hydrogen can be produced from renewables, nuclear, natural gas, coal, and oil. It can be transported as a gas by pipelines or in liquid form by ships, much like LNG. Additionally, it can be transformed into electricity and methane to power homes and industry, as well as into fuels for cars, trucks, ships, and planes.[21]

A low-carbon hydrogen economy, beyond petrochemical and transportation sectors, will require fossil fuels to support emerging carbon- neutral market opportunities like utility-scale, hydrogen-based power generation coupled with energy storage; steel and advanced alloys manufacturing; cement, fertilizer and chemicals production; fuel use for marine, rail, and heavy-duty vehicle applications (i.e., transportation); and renewable power generation for a variety of electrical applications.

While the United States does not currently export hydrogen in significant amounts, global initiatives to reduce CO_2 emissions could expand global trade of the resource. Japan, South Korea, and China have made significant progress in hydrogen development, setting ambitious targets for 2030 by viewing hydrogen as a means of managing environmental concerns without weakening energy security. Countries that have released a national hydrogen strategy include the Netherlands, Norway, Portugal, Japan, South Korea, Australia, New Zealand, and Germany. Most recently, a Canadian government agency, Natural Resources Canada, confirmed that it is developing a national hydrogen strategy.[22] In addition, the European Commission released its hydrogen strategy in July 2020.[23]

Hydrogen Transportation

Hydrogen transportation, distribution, and storage are the primary challenges for integrating hydrogen into the overall energy economy system. On a mass basis, hydrogen has nearly three times the energy content of gasoline. While hydrogen has high energy density per unit mass, it has low-volumetric energy density at room conditions (around 30% of methane at 15 °C, 1 bar) and an ability to permeate metal-based materials, which can present operational and safety constraints. This makes transporting hydrogen a challenge because it requires high pressures, low temperatures, or chemical processes to be stored compactly.[24]

Gaseous hydrogen is usually transported by either tube trailers or pipelines, while liquid hydrogen is moved by road tankers. Liquid hydrogen shipping is also being considered as a means for transporting large volumes between countries.

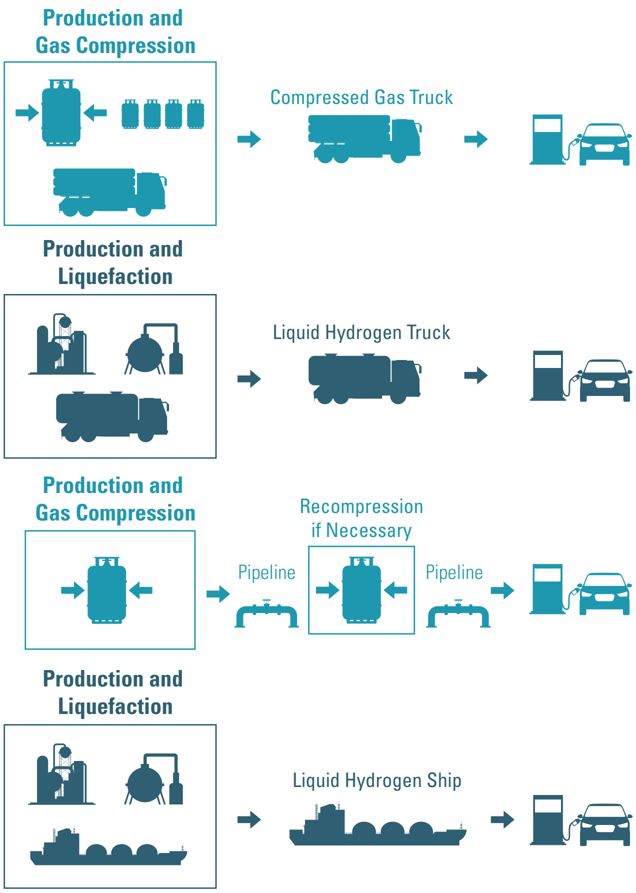
Depending on transportation distance and volumes, trucking may be preferred for short distances and small volumes, while liquid tankers or pipelines are more economical for long distance, larger volume transport. Figure 9 illustrates the primary means of hydrogen transportation.[25]

Pipelines: Existing domestic natural gas pipeline infrastructure has the potential to expand the transportation of hydrogen.[c] Blending hydrogen into natural gas pipeline networks may be an option for delivering pure hydrogen to markets, using separation and purification technologies downstream to extract hydrogen from the natural gas blend near the point of end use.

It is necessary to assess multiple factors to safely integrate hydrogen blending into the existing natural gas pipeline systems (e.g., gaseous hydrogen embrittlement).[d] Notionally, pipelines can handle from 15%–30% hydrogen blends without modifications or significant detrimental effects.[e] While hydrogen compression can be utilized for transport and storage, this compression comes with energy penalties up to 20% of the energy content required for compression.[26]

Trucking: Hydrogen that is transported via truck is typically hauled in either liquid tanker trailers or tube trailers. High-pressure cylinders and tube trailers at ~2,600 pound-force per square inch (psi) are commonly used to distribute gaseous hydrogen within 200 miles of the source. Hydrogen transport by truck typically involves high-pressure tube trailers that operate at pressures twice the amount of normal transporting pressures. Liquid tanker trailers are used for transport distances up to 600 miles. Cryogenic liquid hydrogen trailers operate at near atmospheric pressure.[27]

Figure 9. Primary Means of Hydrogen Transportation



Other: Compared to trucks, it could be more economical to transport hydrogen by railcars, barges, or ships for larger quantities of hydrogen. By utilizing the same style of tube or liquid tanks used by trucks, these modes of transport are not restricted by weight requirements encountered on roadways. The first liquid hydrogen transport ship was launched as a pilot in Japan at the end of 2019, with an anticipated storage capacity of 1,250 m^3 (less than 1% of typical LNG carriers). It is expected that the next version will have greater capacity.

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[c] The natural gas pipeline network within the United States is a highly integrated network that moves natural gas across about 3 million miles of mainline to end-user markets and other pipelines between natural gas producing areas and storage facilities with consumers. Within this network, over 1,600 miles of pipeline are dedicated to the transmission of hydrogen, representing the largest total of dedicated hydrogen pipeline system worldwide (57% as of 2016).

[d] Gaseous hydrogen embrittlement refers to the degradation of fatigue and fracture resistance of structural materials due to exposure to gaseous hydrogen.

[e] Minor detrimental effects can include increased transmission costs and a slight reduction in the overall quantity of energy delivered due to lower volumetric energy density of hydrogen as compared to natural gas.

Hydrogen Storage

Today, hydrogen is most commonly stored as a gas or liquid in tanks for small-scale mobile and stationary applications. Hydrogen storage options include compression or cryogenic systems (or their combination), chemical production systems (such as ammonia), nanomaterial-based storage, and geologic storage. Compression and cooling systems are required for transportation and storage of hydrogen. A variety of metal tanks are typically found at production facilities, transport terminals, and end-use locations. While cryogenic systems are the most common way to store large amounts of hydrogen, advancements in porous nanomaterials may provide another storage mechanism. Within these structures, hydrogen can be stored in non-reactive media, at low-temperature, and with quickly reversible adsorption/desorption of hydrogen without requiring thermal energy. Storing hydrogen as ammonia, conversely, requires thermal energy to decompose the molecules when the hydrogen is needed. Hydrogen storage is a key technological barrier to the development and widespread use of fuel cell technologies in transportation, stationary, and portable applications.

Large-scale hydrogen value chains in the future will require a much broader variety of storage options. In general, geological storage in many regions of the country is the best option for large-scale and long-term storage, while tanks are more suitable for short-term and small-scale storage. Geologic storage within salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs can also be used as long-term storage mechanisms. Further work is required to characterize this opportunity and validate these formations through R&D, geologic characterization, and validation of reservoirs. Storage efforts will be coordinated with EERE which has led the National Storage Project and has substantial ongoing activities.[28, 29]

Office of Fossil Energy

While the overall DOE Hydrogen and Fuel Cells Program[30] describes activities of various offices including EERE, NE, and Science, this document focuses on FE activities. FE's Office of Clean Coal and Carbon Management (CC&CM) and Office of Oil and Natural Gas (ONG) are the two programs currently leading fossil energy-based hydrogen related R&D. Their past, current, and planned areas of research are described below.

Office of Clean Coal and Carbon Management Hydrogen R&D Program

CC&CM is focused on advancing the technologies needed to produce hydrogen from coal-derived synthesis gas to build and operate carbon-neutral, high-efficiency, poly-generation facilities, such as those being considered under the Coal FIRST program.[31] Many of the past and current CC&CM R&D programs directly align with producing and utilizing hydrogen. For example, oxygen separation, gasification, catalysis, separations and materials science, and process engineering are key CC&CM strengths that will have a fundamental role in the production of hydrogen. Turbines, fuel cells, materials science, combustion science, catalysis, chemistry, and fuel science all enable the transport, storage, and utilization of hydrogen. FE is also the global leader on key technologies such as emissions controls and CCUS. These technologies will be critical to producing carbon-neutral hydrogen from carbon-containing feedstocks, as well as to developing highly integrated gas turbine hydrogen producing systems with CCUS. Many of these technologies are being integrated into the Coal FIRST program and power generation systems for the 21st Century. Coal FIRST has several gasification systems, which could produce hydrogen for power or poly-generation of chemicals.

FE has previously supported the development of hydrogen turbines for coal gasification systems with pre-combustion carbon capture. This approach, with a water gas shift, produces a pure hydrogen fuel for the gas turbine and was also considered for fuel cell applications. More recently, the focus has been on high hydrogen, content-fueled (70%–100% hydrogen) turbines. In this application, combustion characteristics pose a challenge. Hydrogen is a fast-burning fuel with high flame speeds, causing issues with most modern dry low-nitrogen oxides (NO_x) combustors on industrial gas turbines. Previous DOE-funded research investigated issues related to hydrogen use in turbines and its effects on combustion, materials, and aerothermal heat transfer. Significant progress was made in resolving the understanding of auto-ignition, flashback, thermo-acoustics, mixing requirements and other combustion-related phenomena.

A significant amount of work remains before a full commercial offering of 100% hydrogen-fueled turbines. After the hydrogen concentration exceeds 75%, there is a significant change in combustion behavior that will require new combustor designs, sensor locations, and control schemes to detect the flame and monitor for flashback and thermo-acoustic instabilities. NO_x emissions will become an issue at higher hydrogen concentrations due to increased flame temperatures and limitations of current pre-mixed dilution technologies. Standard catalytic NOx reduction technologies with some modifications could still be a viable approach. The higher flame temperatures and increased water content could also affect the lifetime of metal hot gas path parts and ceramic recession, thereby increasing the need for new materials and coatings and improved cooling schemes.

The remaining issue for high hydrogen operations is fuel flexibility. If hydrogen is blended into natural gas pipelines, then it is unlikely that the mix will be steady and predictable. This would have to be mitigated through regulation by network operators, or it would require faster fuel composition analysis built into turbine control.

Office of Oil and Natural Gas Hydrogen R&D Program

The proximity and use of hydrogen for industrial processes related to oil and natural gas provides an opportunity for ONG to leverage existing R&D toward enabling the future hydrogen economy, its markets, supply infrastructure, transportation, storage, and use for industrial purposes and power generation. Natural gas networks are well developed in the United States and represent infrastructure that could be adopted for conveyance of hydrogen. While converting natural gas infrastructure to hydrogen infrastructure is a long-term proposition, transition strategies call for the introduction of hydrogen into the existing natural gas infrastructure. This strategy is being pursued by other countries, although significant questions remain regarding safety associated with hydrogen transport. There are many unknowns about the suitability of materials for hydrogen service in natural gas distribution systems; however, ONG and its partners have an existing and expanding transportation and storage infrastructure R&D portfolio that is relevant to a comprehensive hydrogen economy strategy.

ONG is currently centered on developing processes to convert flared or vented gas to hydrogen products to include modular hydrogen production from natural gas streams and utilizing hydrogen for upcycling methane into other higher-value products. ONG's efforts in this area are being pursued via hydrogen-related R&D under a Funding Opportunity Announcement (FOA), "FE FOA2006 – Advanced natural gas infrastructure technology development process-intensified technologies for the upcycling of flare gas into transportable, value-added products." Through the selections made under the FOA in January 2020, FE is currently expanding its research program focused on mitigating emissions from midstream natural gas infrastructure.

Accelerating the Hydrogen Economy with Future R&D

Since 2005, FE invested in the development of hydrogen turbines for coal gasification systems with pre-combustion carbon capture. Using coal gasification with a water gas shift approach produces a pure hydrogen fuel for the gas turbines in fuel cells and other applications. Industry embraced technology development for hydrogen-fueled turbines, which resulted in upgraded components for commercially available turbines and potential retrofits for the existing fleet. All major turbine manufacturers have committed to capabilities of at least 20% hydrogen combustion by 2020 and 100% hydrogen combustion by 2030. However, a significant amount of work remains (e.g., additional combustor development) before the full commercial offering of 100% hydrogen-fueled turbines, which could have technology applications to multiple sectors, such as the aviation industry.

Reversible SOFCs can be a source of efficient, low-cost electricity from natural gas or hydrogen for baseload and distributed power generation. The high operating temperatures of SOFCs offer the possibility of internal reforming of methane, providing additional sources of hydrogen production. Thus, SOFCs with internal reforming can enable the hydrogen economy by producing hydrogen at scale within a carbon-capture-ready paradigm through simple condensation of the SOFC exhaust.

FE has been advancing technologies to produce hydrogen from coal and natural gas, but more work is needed in this area. Hydrogen from natural gas is commercially viable today and it could be a bridge technology with CCUS to enable future energy scenarios where hydrogen is sustainably produced using all of the diverse domestic resources, but need to reduce the capital costs and improve the efficiency of these technologies to be competitive. Major investments in R&D over the next 5 years can help accelerate and address several key areas that could enable the transition to a hydrogen economy. In addition, more work is required on natural gas-to-solid carbon plus hydrogen, which offers a valuable byproduct and additional revenue streams for new markets. FE's depth of experience, previous R&D, and future efforts can be summarized in four major focus areas:

1. **Carbon-Neutral Hydrogen Production using Gasification and Reforming Technologies**
    - Develop advanced gasification materials, components (gasifier, cleanup systems, membranes, catalysts), and systems (small- and large-scale plasma, thermal, and microwave) with CCUS that can accept multiple fuels (coal, biomass, and waste plastics) to produce low-cost, carbon-neutral hydrogen.
    - Support advanced steam methane and auto-thermal reforming technologies with CCUS to provide near-zero hydrogen to the economy, and convert waste gaseous hydrocarbons to hydrogen using similar modular technologies. FE will lead methane-related hydrogen production activities and/or R&D.

- Develop pre-combustion CO_2 capture technologies (advanced solvents, solid sorbents, and membrane systems) for hydrogen production processes to demonstrate zero-carbon or negative-carbon emissions from fossil fuel, biomass, and waste plastics hydrogen production.
- Develop CCUS technologies, including pre- and post-technologies for power and the industrial sector, as well direct air capture technologies, that can remove CO_2 from the atmosphere (FE is leading DOE's efforts in this area).

2. Large-Scale Hydrogen Transport Infrastructure

FE has been involved in decades of research on the materials, design, and infrastructure to support 3 million miles of existing natural gas pipeline network, including mainline and other pipes transport linking production and storage facilities with customers. More recently, FE has been working with industry and partnering agencies on monitoring and mitigation technologies to quantify and eliminate fugitive emissions from the oil and natural gas pipeline networks. Additionally, FE continues to invest in projects to address design and materials requirements for blending hydrogen into the existing natural gas infrastructure and ultimately replacing natural gas with hydrogen, in coordination with EERE. Specific R&D activities coordinated with EERE and other offices include the following:

- Assess pipeline performance for fatigue and fracture resistance of metallic materials in natural gas networks as related to the embrittlement issue and ensure their compliance with appropriate standards and codes.
- Develop new components, configurations, and sensor technologies combined with artificial intelligence for real-time operational monitoring and early fault detection for the safe transport of hydrogen in commerce.
- Develop design requirements and typical operating conditions in natural gas supply infrastructure, as well as identify and prioritize materials performance gaps to avoid leakage within pipeline elements, such as joints, valve and flange connections, gas meters, and compressors to safeguard operations.
- Conduct hydrogen transportation and storage infrastructure assessments and R&D (e.g., materials, geology), conduct resource assessments, and establish field laboratories for hydrogen storage.
- Evaluate and regulate hydrogen export policies and procedures.

3. Large-Scale Onsite and Geological Hydrogen Storage

FE is the leading organization on storage of natural gas in geologic formations and characterization for geologic storage of CO_2, as well as the operator of the Strategic Petroleum Reserve. The experience and personnel in these areas can be leveraged to accelerate the development and deployment of large-scale hydrogen storage in the United States. FE has also led the work on other geologic resources such as coal bed/mine methane, enhanced oil and gas recovery, and the characterization of rare earth elements and critical materials. In addition, over the past several decades, FE has been managing the gasification and pre-combustion capture programs, which have included efforts to produce pure hydrogen and synthesize chemicals, such as ammonia and other fuels. Leveraging this experience, FE will focus on the following activities:

- Characterize regional geology, infrastructure requirements, and materials of construction for the storage of hydrogen in geologic formations, including salt domes, depleted oil and gas reservoirs, and natural gas storage sites.
- Develop advanced storage materials and systems for large-scale hydrogen storage to support the electricity industry and poly-generation.

- Develop pipeline technologies and components for blended natural gas hydrogen mixtures to ensure reliable delivery within existing natural gas infrastructure.
- Develop conversion technologies (catalysts, materials, and processes) to utilize hydrogen for added value products and/or chemical production, specifically ammonia, to store days' worth of energy for future electricity production.

4. Hydrogen Use for Electricity Generation, Fuels, and Manufacturing

For over 20 years, FE has been developing advanced power systems (e.g., turbines) and SOFCs to utilize blended hydrogen and natural gas or pure hydrogen to generate carbon-neutral electricity. Decades of experience on these systems and future research can enable wide-scale deployment of hydrogen generation technologies such as hydrogen turbines and reversible SOFCs. Additionally, the materials and some of the processes from these technologies can be adapted and used for other industrial uses (e.g., aircraft engines, trains). The following research activities are planned:

- Develop technology for hydrogen-fueled turbines for potential retrofits or enhancements to internal combustion engines, industrial gas turbines and combustion systems for power generation, and transportation (ground, air, and marine).
- Develop Solid Oxide Cells to operate as an electrolyzer (SOEC) for production of hydrogen for storage and reversible systems to operate as an SOFC when electricity production is in high demand, leveraging 20 years of FE- sponsored R&D on SOFC systems.
- Ensure specification and safety standards developed for utilization of hydrogen or derivative chemicals in the refining, metallurgical, food processing, cement, transportation, and other sectors.
- In addition, FE has previous experience in hydrogen handling and can leverage efforts on LNG export licensing reviews to identify safety and export terminal requirements. This will support efforts to export to hydrogen economies where hydrogen can be used for electricity generation, manufacturing, transportation, and residential purposes.

Safety and Regulatory Requirements and Challenges

Increasing the use of hydrogen and exploring new processes for the production and use of hydrogen using the existing gas distribution and storage infrastructure will require identification of and responses to several safety issues. Recent studies on market penetration of hydrogen anticipate many applications, which will require considerable additions to the transportation and storage infrastructure. Some of these will result in new safety concerns that need to be addressed.

According to a 2013 report published by the National Renewable Energy Laboratory,[32] blending hydrogen into natural gas pipeline networks has been proposed as a means of delivering pure hydrogen to markets using separation. Separation and purification technologies will be used downstream to extract hydrogen from the natural gas blend close to the point of end use. As a hydrogen delivery method, blending can defray the cost of building dedicated hydrogen pipelines or other costly delivery infrastructure during the early market development phase. However, blending hydrogen can materially degrade pipelines designed for natural gas (via hydrogen embrittlement).[33] The risk involved depends on the specific types of materials used throughout the transportation and distribution systems.

The impact of adding hydrogen into the pipeline systems would also depend on the hydrogen concentration in the gas mixtures.[34] If less than 20% hydrogen is introduced into the distribution system, the overall risk is not significant. If the hydrogen level in natural gas increases beyond 20%, the overall risk in service lines can significantly increase, absent additional risk management measures.[35] Construction of new pipelines, either natural gas pipelines that will be used for a blended gas or hydrogen dedicated lines, will require consideration of the challenges that hydrogen poses during transportation by pipeline. Adequate safety provisions can be made if there is a thorough understanding of these risks.

If the amount of hydrogen being produced and utilized is to increase substantially, storage near the site of production and storage near end uses are likely to be required. Analogies to this situation already exist for natural gas, but steps to address novel safety considerations, revised regulations, and tightened design standards may be needed. Solution-mined salt caverns, depleted natural gas or oil reservoirs, and saline aquifers are considered possible options for large-scale and long-term hydrogen storage. These storage options are currently used for natural gas storage.

Currently, several existing U.S. and international standards allow the safe use, distribution, and storage of hydrogen. These standards are focused on the current hydrogen infrastructure, including building codes, fire codes, and items pertaining to technologies used to transport and store hydrogen.[36] Within the United States, interest in hydrogen in the first decade of this century led to the passage of several laws that created financial incentives and regulatory requirements. Several states have passed laws to encourage development of stationary hydrogen applications.[37] These acts establish provisions for tax incentives aimed at promoting infrastructure development that supports hydrogen stationary power technologies. In addition, there are production tax credits based on the amount of electricity produced from stationary hydrogen power sources.[38]

Looking toward an expanded hydrogen infrastructure, it is important to note that globally, the state of existing regulations and standards currently limits hydrogen uptake. Certain regulations are unclear or not written with new uses of hydrogen in mind. Therefore, they do not allow exploitation of the full benefits hydrogen can provide. These regulations need to be updated if hydrogen is to have the opportunity to fulfill its potential.

For the United States, it is important to identify the options being pursued and to ensure that essential standards and regulations exist to cover these nascent applications (processes, infrastructure, and end use). The current framework provides a sound basis, but gaps have been recognized, and critical needs should be addressed during the developmental phase of new technologies in coordination with EERE.

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U.S. DEPARTMENT OF
ENERGY

July 2020

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