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The Hydrogen Economy: Putting the Pieces Together

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SUMMARY

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Martin C. Offutt
Analyst in Energy Policy

A future economy using hydrogen as an energy carrier and fuel has been a topic among policymakers evaluating whether hydrogen could offer an alternative to the current system that provides modern energy services primarily with fossil fuels. In addition to transportation fuel—one of the larger applications envisaged—hydrogen may support industrial processes or building operations or store energy. Cost and performance of hydrogen-utilizing technologies and their technological readiness are not on par with current energy technology, and any transition would have its own costs.

Hydrogen has various applications in industry. For example, refineries annually use roughly 38 million metric tons (Mt) of hydrogen and the rest of industry 51 Mt, worldwide, for its chemical properties. "On purpose" hydrogen does not deliver energy services in commercial quantities. By-product hydrogen is used in some industrial applications for its energy. A hydrogen economy might help unlock the potential of fuel for personal mobility, high-temperature heat for manufacturing, thermal comfort in buildings, and other modern uses of energy.

Hydrogen is present but diffuse in the lithosphere and does not exist in convenient reservoirs, necessitating its production from chemical feedstocks or water. The primary resource providing the energy and chemical constituents is mainly natural gas but in the future might include renewable or nuclear energy to electrolyze or "split" water into hydrogen. Depending on the method of production, addressing carbon emissions and pollutants may necessitate gas cleanup and capture. In addition to production, other pieces of a hydrogen economy include:

- An energy carrier—e.g., hydrogen, ammonia, electricity—which moves long distances and, as appropriate, is converted to hydrogen and stored near the point of use such as at a refueling station or power plant; and
- The technology, such as a fuel cell or engine, that converts the carrier into useful energy to provide a service—mobility, electric power, heat for industrial applications, and so forth.

Potential hydrogen applications are in many sectors of energy consumption. Some focus on established energy applications and target the replacement of the fuels currently in use—for example, the replacement of petroleum-fueled internal combustion engines with hydrogen-consuming fuel cell vehicles. Further examples include the use of hydrogen in steelmaking and, in manufacturing, for high-temperature heat to support various processes; as an energy storage medium in electric power; and as a substitute for natural gas in residential buildings.

The potential carbon dioxide and pollutant emissions from use of hydrogen applications depend on the production method. The use of non-emitting electricity offers lower carbon dioxide (CO_2) emissions and lower pollutant emissions relative to current fuels. An analysis of the technology readiness of these replacement applications to enter widespread deployment shows that some have achieved early commercial status while others are still at demonstration phases. Overall, a hydrogen economy faces challenges of scaling up for industrial production, mobilizing capital, permitting and regulatory approvals, and the practical aspects of building or retrofitting facilities. Current hydrogen costs at the pump are estimated in the \$12-\$13 per kilogram (kg) range, while, to be competitive with incumbent technologies, the cost of hydrogen would need to be in the range \$3-\$6/kg at the pump.

Congress has taken some steps to accelerate the scale-up of a hydrogen economy. The Regional Clean Hydrogen Hubs, funded and authorized in the Infrastructure Investment and Jobs Act (IIJA, P.L. 117-58) at \$8 billion for at least four such hubs, are intended to yield insights and validate the claimed benefits (environmental and otherwise) and identify technology needs and readiness. Some options for Congress that might further support scale-up toward a hydrogen economy or accelerate the development of specific applications, if desired, include expanding loan guarantee authority for hydrogen production projects or siting authority for hydrogen pipelines. Congress may also conduct oversight of the funding added in the IIJA, including the Department of Energy's award of the first tranche of funding for the hydrogen hubs.

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Introduction

A future economy using hydrogen as an energy carrier[1] and fuel has been a topic among policymakers evaluating whether hydrogen could offer an alternative to the prevalent combustion of fossil fuels now used to provide modern energy services. Past analyses have associated hydrogen with mobility applications, especially light-duty vehicles (LDVs) powered by fuel cells in which hydrogen and atmospheric oxygen combine to provide electric power while giving off only heat and water.[2] In addition to providing a fuel for transportation, hydrogen could become part of the energy infrastructure by storing energy or it could provide an alternative fuel to meet demand for thermal comfort in buildings or high-temperature heat in industry. Other value propositions include industrial applications such as steelmaking, in which pure hydrogen could replace the current mixture of chemical reducing agents, and emerging applications such as portable power.[3] The rationale analysts and policymakers provide for hydrogen is its merit with respect to emissions;[4] if used in a fuel cell, hydrogen does so with zero emissions of pollutants at the point of end use.[5] Hydrogen may be produced from a diversity of feedstocks, potentially making supply more assured and less vulnerable to disruptions were supply of any one feedstock to be curtailed.

The fuel for the hydrogen economy is the basic molecule of hydrogen (H_2), two hydrogen atoms bound together. Much of the hardware required to operate a hydrogen economy employs technologies that handle such molecular hydrogen. A power source currently being tested for automobiles, the polymer electrolyte membrane (PEM)[6] fuel cell, uses hydrogen and atmospheric oxygen to create electric power and water vapor. While some devices such as the PEM fuel cell call for neat (pure) hydrogen fuel, others can use hydrogen blended with methane in a combustion turbine, a type of engine found in electric power stations. Hydrogen is also being investigated for distribution in existing natural gas pipelines, blended with methane.[7] A hydrogen economy could thus be a combination of the old with the new.

Hydrogen is present but diffuse in the lithosphere and does not exist in convenient reservoirs, meaning it must be produced from chemical feedstocks or water. The predominant methods today employ fossil fuels and occur at large-scale industrial facilities.[8] In the United States, hydrogen is mostly produced using a multi-step process starting with steam methane reforming (SMR) of de-sulfurized natural gas, followed by production of additional hydrogen using the non-hydrogen

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[1] Energy carriers are substances or physical phenomena such as electricity that have potential energy, allowing them to perform work or provide heat or light, and that can be transmitted over long distances without substantially losing their potential energy.

[2] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, Washington, DC, 2004.

[3] Emiliano Bellini, "Portable Hydrogen Fuel Cell Generator with Power Output of 400 W," *PV Magazine*, July 14, 2021; PowerUP Energy Technologies, *Our Products*, 2022, https://powerup-tech.com/shop/.

[4] "Clean fuel" lacks a widely used, technically precise definition of clean fuel. Section 40315 of the Infrastructure Investment and Jobs Act (IIJA, P.L. 117-58) defined "clean hydrogen" as being hydrogen produced with 2 kilograms or fewer of carbon dioxide equivalent per kilogram of hydrogen ($\leq$ 2 kg-CO_2-eq/kg-H_2).

[5] The lifecyle emissions associated with converting primary energy into hydrogen and transporting the product, as well as direct hydrogen emissions (e.g., leakage during storage or transport) may still be a factor.

[6] Or, equivalently, the proton exchange membrane (PEM).

[7] Kiwa Gastec and Amec Foster Wheeler, *H21 Leeds City Gate Report*, Northern Gas Networks, 2016, https://h21.green/projects/h21-leeds-city-gate/.

[8] Globally, natural gas is the feedstock for roughly three-quarters of today's dedicated production of hydrogen and coal roughly one quarter. IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 19.

products of the SMR step. A final step in the process train is to recover hydrogen produced in the earlier steps to a higher level of purity.[9] Other methods employ water as a feedstock and use an electrochemical device to decompose water into hydrogen and oxygen ("electrolysis" or "water splitting"). A variant on this method, high-temperature electrolysis (HTE), uses high temperature steam as the feedstock; technologists have built demonstration-scale HTE plants using nuclear energy as the heat source for the steam.[10] A further method already in large-scale use involves heating coal or biomass to high temperatures.[11]

Analysts have evaluated methods of producing hydrogen using electricity from non-extractive, non-emitting resources. Such methods again decompose water into hydrogen using electrochemical methods. Some of these are referred to as "green hydrogen," generally for wind, solar, or hydroelectric power. Non-emitting "pink hydrogen" occurs when nuclear generation is the source of the electricity.[12] The colors associated with different ways of producing hydrogen are discussed in a text box, below.

Hydrogen Production and "Hydrogen Colors"

With climate change as a consideration for the production of electricity, much attention has turned to the use of hydrogen as a fuel, since the use of hydrogen in a fuel cell generally produces only water vapor as a by-product. However, most hydrogen produced today does not come from processes that are free from carbon emissions. Carbon-free hydrogen can be produced by using renewable electricity or other fossil-free electricity sources (which potentially includes nuclear power) to power an electrolyzer—an electrochemical device, powered by electricity, that decomposes water into hydrogen and oxygen. Hydrogen produced via electrolyzers is generally referred to as "green hydrogen" if the source of electricity is renewable or otherwise emissions-free. This method accounts for about 3% of hydrogen produced today. Today's steam methane reforming (SMR) process releases about 10 kilograms (kgs) of carbon dioxide per kg of hydrogen produced. Hydrogen produced by SMR is often referred to as "gray hydrogen" since these carbon emissions are largely vented to the environment. "Blue hydrogen" results when the carbon released from a steam reforming process is captured and stored (i.e., carbon capture, utilization and storage (CCUS)), either for reuse in another industrial process or sequestered underground in mines or caverns. Blue hydrogen is sometimes referred to as "carbon neutral" as the emissions are not dispersed in the atmosphere. Some argue that "low carbon" would be a more accurate description, as they report that 10%-20% of the generated carbon emissions cannot be captured. "Pink hydrogen" refers to hydrogen created through electrolysis of water powered by nuclear energy rather than renewables. Other less well-defined terms such as "yellow hydrogen" continue to emerge through stakeholder use. Other observers use the term to describe hydrogen generated through electrolysis of water using mixed sources of electricity, based on what is available. There are other terms associating specific colors with how hydrogen is produced; see https://www.cummins.com/news/2021/11/16/what-hydrogen-rainbow.

This report discusses the current uses of hydrogen; some examples of applications that would offer value propositions in a possible hydrogen economy; discussion of the potential benefits and technology readiness, costs, and potential obstacles; the outlook for deployment; some recent developments; and issues for consideration by Congress.

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[9] National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, Washington, DC, 2004, p. 199.

[10] Idaho National Laboratory has developed a 25 kilowatt (kW) HTE test facility. H. Hogan, INL Communications and Outreach, *A Step Closer to Clean Hydrogen*, Idaho National Laboratory, March 5, 2021, https://inl.gov/article/a-step-closer-to-clean-hydrogen/.

[11] For more information, see CRS Report R46436, *Hydrogen in Electricity's Future*, by Richard J. Campbell.

[12] Cummins, Inc., *What is the Hydrogen Rainbow?* November 16, 2021, https://www.cummins.com/news/2021/11/16/what-hydrogen-rainbow.

Hydrogen Today: Scope and Scale

The envisaged hydrogen economy could see hydrogen produced in many possible ways, some of which are in widespread use. Petroleum refineries use hydrogen to remove sulfur and other contaminants, and to change the chemical composition of the crude oil when making *product* such as gasoline. Refineries and chemical manufacturers in some instances produce their own hydrogen, utilized at the same site where it is made. A merchant hydrogen sector manufactures hydrogen and sells it to various concerns including refineries and chemical manufacturers. Complementing this 'on-purpose' use of hydrogen is by-product hydrogen, referring to the hydrogen produced in a mixture with other chemicals during industrial processes where hydrogen is not the primary commodity.[13]

Refineries used roughly 38 Mt of hydrogen, and the rest of industry roughly 51 Mt, globally, in 2020.[14] Roughly two-thirds of demand in industry, exclusive of refining, was for manufacture of ammonia.[15] Ammonia may have a role as an energy carrier itself, discussed further in "Energy Carriers," below.[16]

In the United States, roughly 10 Mt of on-purpose hydrogen is manufactured annually.[17] The majority—90%—of this hydrogen is manufactured using steam methane reforming.[18] By-product hydrogen can account for several additional Mt.[19] For example, over 40% of the hydrogen consumed in U.S. refineries is a by-product of the reforming of naphtha[20] at refineries.[21] Estimates of the overall quantities of by-product hydrogen vary and hence so do total production figures for all hydrogen, including by-product plus on-purpose.[22] In the United States, hydrogen is generally not being used for its energetic properties, with the exception that roughly 2 Mt annually of by-product hydrogen is combusted for heat in industrial processes.[23]

Figure 1 depicts the relative sizes of the various sources of hydrogen, on the left, with the use cases on the right, on a global basis in 2018. The figure shows hydrogen is important in industry but does not currently deliver energy services to firms and consumers other than in

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[13] A small fraction of by-product hydrogen enters the merchant hydrogen market. D-Y Lee, A. Elgowainy, and Q. Dai, *Life-Cycle Greenhouse Gas Emissions of By-Product Hydrogen from Chlor-Alkali Plants*, Argonne National Laboratory, ANL/ESD-17/27, Argonne, IL, December 2017, p. 1.

[14] IEA, *Global Hydrogen Demand by Sector in the Net Zero Scenario, 2020-2030*, October 26, 2021, https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030.

[15] IEA, *Hydrogen Demand in Industry, 2020*, October 26, 2021, https://www.iea.org/data-and-statistics/charts/hydrogen-demand-in-industry-2020.

[16] For more information, see CRS In Focus IF12273, *Ammonia's Potential Role in a Low-Carbon Economy*, by Lexie Ryan.

[17] Sunita Satyapal, Director, DOE Hydrogen and Fuel Cell Technologies Office, *2022 AMR Plenary Session*, June 6, 2022, at https://www.energy.gov/sites/default/files/2022-06/hfto-amr-plenary-satyapal-2022-1.pdf; E. Connelly, A. Elgowainy, and M. Ruth, *Current Hydrogen Market Size: Domestic and Global*, DOE, Record #19002, October 1, 2019, p. 1.

[18] D-Y Lee, A. Elgowainy, and Q. Dai, *Life-Cycle Greenhouse Gas Emissions of By-Product Hydrogen from Chlor-Alkali Plants*, Argonne National Laboratory, ANL/ESD-17/27, Argonne, IL, December 2017, p. 1.

[19] E. Connelly, A. Elgowainy, and M. Ruth, *Current Hydrogen Market Size: Domestic and Global*, DOE, Record #19002, October 1, 2019, p. 1.

[20] Naphtha is a crude oil fraction that separates out from crude during distillation at a certain temperature range.

[21] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 93.

[22] E. Connelly, A. Elgowainy, and M. Ruth, *Current Hydrogen Market Size: Domestic and Global*, DOE, Record #19002, October 1, 2019, p. 1.

[23] D-Y Lee, et al., op. cit., p. 1.

demonstration-scale quantities. In the vision of a hydrogen economy, hydrogen would assume the role of energy carrier and fuel, as opposed to mainly a process chemical.

Funding for the U.S. Department of Energy's (DOE's) hydrogen and fuel cell technology programs received increases in FY2004 to FY2007, peaking at $329.7 million in FY2007. Thereafter funding declined by roughly 40% as of FY2011 before stabilizing at roughly $140 million +/- $10 million. Appropriations increased again to $276.8 million in FY2020 following the addition of programs at ARPA-E (Advanced Research Projects Agency–Energy) and increases in other DOE offices.[24] At the time of the mid-2000s increases, DOE's stated goal was to reach a commercialization decision on fuel cell vehicles in 2015.[25] Hyundai, Honda, and Toyota announced their commercial light duty fuel cell electric vehicles (FCEVs) in 2013.[26] However, the number of light duty FCEVs sold or leased is small compared to the numbers of conventional LDVs, as discussed further in the section "What Could a Hydrogen Economy Do?"

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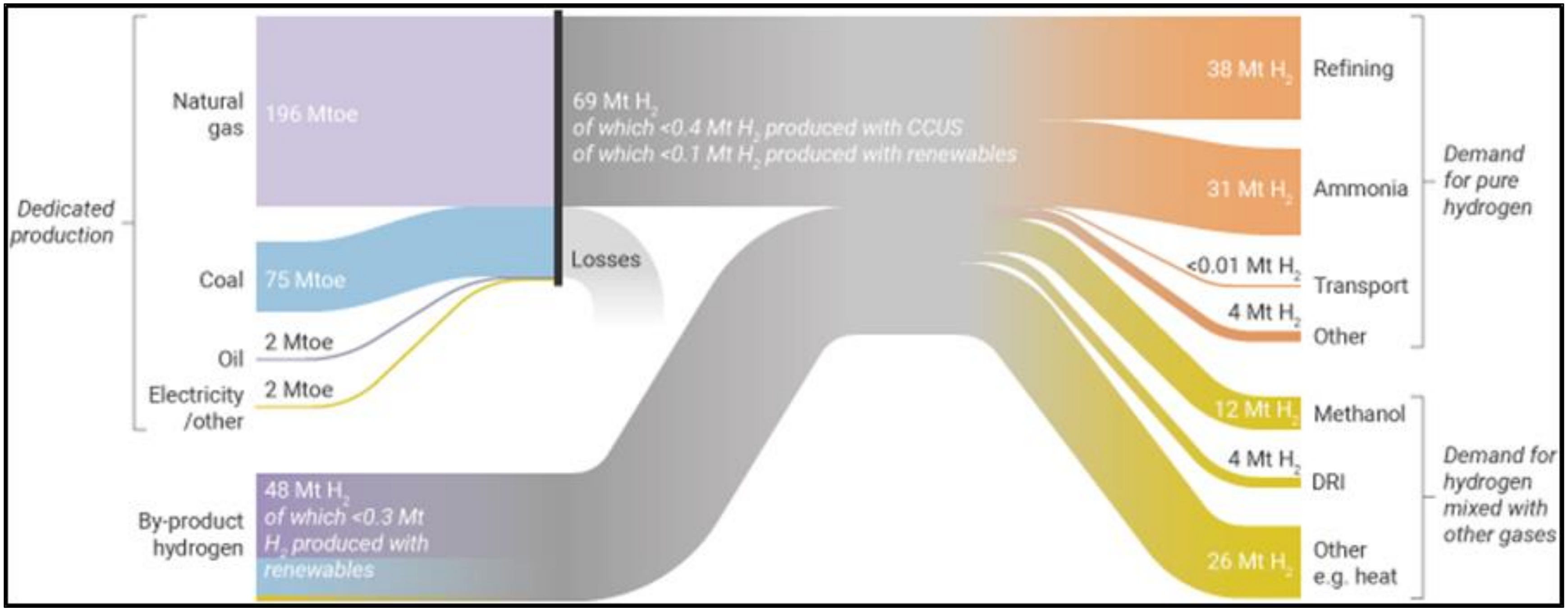
[24] U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, *Hydrogen Program: Budget*, https://www.hydrogen.energy.gov/budget.html.

[25] DOE, *Hydrogen, Fuel Cells and Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan*, Washington, DC, June 3, 2003.

[26] Anne C. Mulkern, "3 Automakers Launch Fuel-Cell Electric Vehicles, Say Market Finally Is Ready," *E&E News*, November 21, 2013.

Figure 1. Hydrogen Value Chains (2018)



Source: Figure 6 of International Energy Agency, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 32.

Notes: CCUS = carbon capture, utilization, and storage; DRI = direct reduced iron; H_2 = hydrogen; Mt = million metric tons; Mtoe = million metric tons oil equivalent, a measure of energy, equal to roughly 7 million barrels of oil or one twenty-fifth of a quad (quadrillion British thermal units). IEA states: "Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g. carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilisation rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted."

Energy Carriers in a Hydrogen Economy

Physical Form

An energy system—hydrogen, electric, or other—requires a means of transporting energy, in whatever physical form, from the point where the primary resource is first converted into the carrier to the point of its conversion to the fuel. For example, for the current transportation system, energy—mostly in the form of petroleum—is converted to gasoline and diesel fuel, which are transported to refueling stations to dispense into vehicles. In a hydrogen economy, the energy carrier could be hydrogen but could also be substances that contain the element hydrogen as part of a chemical compound that is convenient to move around, whether in the form of methane, ammonia, or other substances that have been proposed.[27]

Ammonia is an energy carrier that can be converted into hydrogen. Ammonia is easier to store, package, and transport than molecular (i.e., pure) hydrogen. For comparison, hydrogen storage at room temperature requires high pressure to achieve sufficient energy density (Joules/cubic meter), while ammonia is in liquid form at room temperature with modest compression.[28] When packaged as a liquid, ammonia contains 48% more hydrogen by volume than would liquid molecular hydrogen.[29] Further, there is extensive ammonia infrastructure worldwide: there are 200 harbors with terminals for ammonia servicing an annual global trade of 20 Mt.[30]

Transmission and Distribution (T&D) and Storage

Within the United States, a network of trucks and pipelines currently transports one-third of the 10 Mt of on-purpose hydrogen manufactured annually, with the rest being used at the site of production.[31] The infrastructure for hydrogen transmission in the United States is modest compared with that of natural gas or electricity. U.S. hydrogen pipelines operate mostly in the Gulf of Mexico region and total 1,600 miles,[32] compared with 300,000 miles of natural gas transmission pipelines[33] and nearly 160,000 miles of high-voltage power lines across the

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[27] N.P. Brandon and Z. Kurban, "Clean Energy and the Hydrogen Economy," *Philosophical Transactions of the Royal Society A*, vol. 375, June 12, 2017.

[28] H. Kobayashi, A. Hayakawa, and K.D. Kunkuma, "Science and Technology of Ammonia Combustion," *Proceedings of the Combustion Institute*, vol. 37, no. 1, 2019, pp. 109-133.

[29] D. Erdemir and I. Dincer, "A Perspective on the Use of Ammonia as a Clean Fuel: Challenges and Solutions," *International Journal of Energy Research*, vol. 45, no. 4, March 25, 2021, pp. 4827-4834.

[30] IEA, *Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production*, Paris, October 2021, p. 72, https://www.iea.org/reports/ammonia-technology-roadmap.

[31] D-Y Lee, A. Elgowainy, and Q. Dai, *Life-Cycle Greenhouse Gas Emissions of By-Product Hydrogen from Chlor-Alkali Plants*, Argonne National Laboratory, ANL/ESD-17/27, Argonne, IL, December 2017, p. 1. The estimate of one-third assumes only on-purpose hydrogen is accounted for and that the approximately 3.3 Mt of by-product hydrogen from oil refineries is not used in the denominator of the calculation.

[32] Over 90%, by mile of pipeline, is in Texas and Louisiana with 10 other states having under 35 miles each. DOE, Hydrogen and Fuel Cell Technologies Office, *Hydrogen Pipelines*, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines; Hydrogen Tools, *Hydrogen Pipelines*, https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines.

[33] U.S. Department of Transportation: Pipeline and Hazardous Materials Safety Administration, *Annual Report Mileage for Natural Gas Transmission & Gathering Systems*, May 2, 2022.

continental United States.[34] Globally, most hydrogen pipelines are owned by merchant hydrogen producers who sell their hydrogen to industry in bulk.[35]

The storage of hydrogen at its point of final consumption, terminals, or refueling stations, is complicated by its physical properties. At environmental pressure and temperature, hydrogen is a gas with low energy density.[36] Over 400 cubic feet of hydrogen (1 kg) under such conditions would be needed to equal the chemical energy of one gallon of gasoline.[37] To facilitate the transport of hydrogen and to increase how much can be stored on-board a vehicle, automakers have used compressed hydrogen gas, with or without cryogenic cooling. Still another packaging scheme, the liquefaction of hydrogen, takes more energy owing to hydrogen's very low boiling point[38] and other thermodynamic barriers.

Pieces of a Hydrogen Economy: The Hydrogen Energy Value Chain

Figure 2 shows the conceptual pieces of a hydrogen economy. Hydrogen may be sourced from numerous primary resources (amber), not just today's dominant forms. The hydrogen production step (red) likewise can occur in many ways[39] to make the energy carrier (light blue)—e.g., hydrogen, ammonia, electricity—which is moved long distances and, as appropriate, converted to hydrogen and stored near the point of use. The end-use technology would then convert the carrier (dark blue) into useful energy to provide the energy service (amber). Depending on the method of hydrogen production, there may be an additional step involving gas cleanup and capture (turquoise). The steps related to the energy carrier, transmission and delivery, and storage—light blue in the figure—can occur in different sequences according to which energy carrier is chosen and where along the value chain the hydrogen is produced and stored.

The Infrastructure Investment and Jobs Act (IIJA, §40315, P.L. 117-58) authorized a program of Regional Clean Hydrogen Hubs to demonstrate different parts of the hydrogen energy value chain. Congress appropriated $8 billion (Division J, Title III of the IIJA) for these hubs. In its initial proposal, DOE plans to select six to ten hubs with total funding of up to $6 to $7 billion and 50% cost-share.

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[34] Energy Information Administration, *U.S. Electric System Is Made Up of Interconnections and Balancing Authorities*, July 20, 2016, https://www.eia.gov/todayinenergy/detail.php?id=27152.

[35] IEA, *Global Hydrogen Review*, Paris, 2021, https://www.iea.org/reports/global-hydrogen-review-2021, p. 44.

[36] Energy density, formally the "enthalpy" in this context, takes account of both the heat and the energy needed to expand the gases liberated from burning a given quantity of a substance.

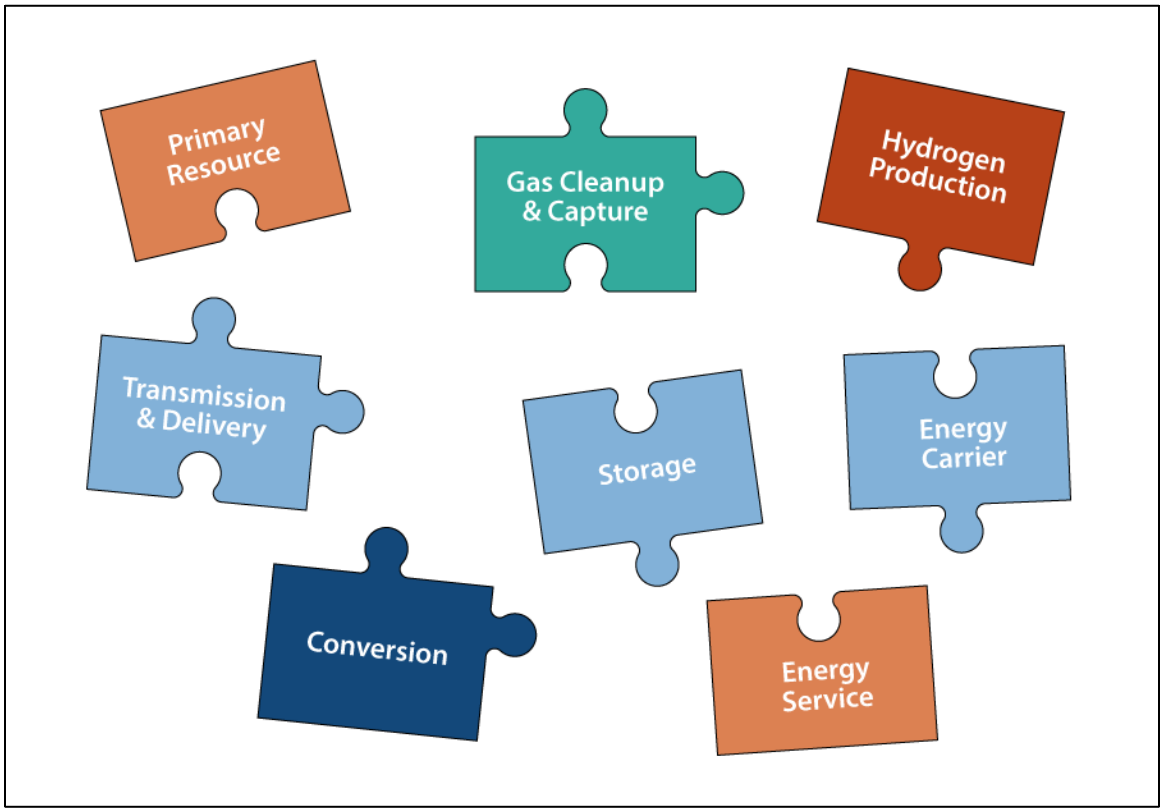
[37] National Institute of Standards and Technology, *Frequently Asked Questions About Commercial Hydrogen Vehicle Refueling*, NIST Weights and Measures, Gaithersburg, MD, September 2019, pp. 6 and 12, https://www.nist.gov/system/files/documents/2020/03/23/nist_h2_faqs-final-03oct2019-h2_website.pdf; National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, Washington, DC, 2004, p. 240.

[38] The boiling point of hydrogen is 20.28 degrees kelvin (K) (-423.17° Fahrenheit). Thomas Jefferson National Accelerator Facility, "The Element Hydrogen," 2020, https://education.jlab.org/itselemental/ele001.html.

[39] See text box, Hydrogen Production and "Hydrogen Colors."

Figure 2. Pieces of a Hydrogen Economy

Energy value chain for a potential future hydrogen energy system



Source: CRS.

What Could a Hydrogen Economy Do?

The following discussion describes selected applications envisaged in a hydrogen economy. The applications do not comprise a comprehensive list, and many additional applications for hydrogen are being proposed. Other studies discuss many of these additional applications.[40]

For statistical purposes, analysts generally organize final consumption or "end use" of energy—the point at which it performs a useful service and is not merely being extracted, refined, transported, or packaged—into three sectors: transportation, industry, and buildings (residential and commercial).[41] This discussion is structured to include hydrogen applications in each of these three sectors. The section also covers an application in the electric power sector—a mid-market segment of the overall energy value chain. Collectively, these four types of applications address

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[40] For multiple examples of applications involving end-use of hydrogen, see CRS Report R46436, *Hydrogen in Electricity's Future*, by Richard J. Campbell; IEA, *Global Hydrogen Review*, Paris, 2022; DOE, *Hydrogen Program Plan*, DOE/EE-2128, Washington, DC, November 2020; Andy Brown, "Uses of Hydrogen, Part 1: Industry," *The Chemical Engineer*, July/August 2019.

[41] K. Riahi, F. Dentener, and D. Gielen, et al., "Chapter 17: Energy Pathways for Sustainable Development," in *Global Energy Assessment—Toward a Sustainable Future* (Cambridge, UK and New York, NY, USA: Cambridge University Press, 2012), p. 1228; T. Bruckner , I.A. Bashmakov, and Y. Mulugetta, et al., "Energy Systems," in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, (Cambridge, UK and New York, NY, USA: Cambridge University Press, 2014).

each of the criteria for end-use diversity Congress specified in §40314 of the IIJA for Regional Clean Hydrogen Hubs.

The applications described here involve a substitution strategy in which an application currently using fossil fuels switches over to using hydrogen. The discussion of each application characterizes the pieces of the hydrogen energy value chain needed to deliver the energy service. In addition, the discussion illuminates potential opportunities and challenges.

Transportation Sector—Personal Mobility

Fuel cell electric vehicles (FCEVs) and other hydrogen vehicles can provide personal mobility. Hydrogen can, depending on the primary resource and its method of conversion, reduce the carbon intensity[42] per passenger mile of mobility, which is analyzed in the section "Potential Environmental Benefits and Drawbacks of a Hydrogen Economy." Automotive original equipment manufacturers (OEMs), currently including Hyundai and Toyota, have produced LDVs using hydrogen as an alternative fuel.[43] Honda ended production of the Clarity Fuel Cell vehicle in 2021.[44] FCEVs use a fuel cell to power an electric traction motor and to drive other loads such as accessories and parasitic loads—the pumps, compressors, and fans necessary for vehicle operation. Car makers had sold or leased nearly 15,000 light-duty FCEVs in the United States, cumulative through December 31, 2022,[45] with over 12,000 of these on the road at the end of 2021.[46] OEMs have also issued concept cars that use hydrogen fuel in an internal combustion engine vehicle (ICEV).[47] Recent developments in FCEVs have addressed customer attributes including acceptable noise, vibration and harshness; sufficient acceleration and top speed; and ride quality.[48]

FCEVs nonetheless require a fuel and an infrastructure to deliver that fuel to a convenient dispensing point. Accomplishing this may require a change from the topology of today's hydrogen transmission and delivery methods (see **Figure 3**), which were built to deliver hydrogen to large industrial users. **Figure 4** shows a possible value chain for hydrogen made in large, centrally located electrolyzers[49] and delivered to refueling stations for FCEVs. Other schemes are possible, and, for example, numerous small electrolyzers could produce hydrogen at or near the

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[42] Carbon intensity can be measured in tons of CO_2 equivalent per megawatt-hour (tCO2-eq/MWh) or also with another unit of energy in the denominator, for example, tCO_2-eq per Joule (tCO_2-eq/J).

[43] "After Many False Starts, Hydrogen Power Might Now Bear Fruit," *The Economist*, July 4, 2020 (updated January 27, 2022), https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit.

[44] Honda, "Fuel Cell Technology Will Continue to Play a Role in Our EV Strategy," press release, June 16, 2021, https://hondanews.com/en-US/releases/release-53541be6030b25a47a2899aba12d4f66-fuel-cell-technology-will-continue-to-play-a-role-in-our-ev-strategy.

[45] California Fuel Cell Partnership, *By the Numbers: FCEV Sales, FCEB, and Hydrogen Station Data*, December, 2022, at https://cafcp.org/by_the_numbers.

[46] R.C. Samsun et al., "Deployment of Fuel Cell Vehicles and Hydrogen Refueling Station Infrastructure: A Global Overview and Perspectives," *Energies*, vol. 15, no. 4975, July 7, 2022, p. 5.

[47] D. Vanderwerp and S. Siler, "2007 BMW Hydrogen 7," *Car and Driver*, September 1, 2006, at https://www.caranddriver.com/news/a15147892/2007-bmw-hydrogen-7-car-news/.

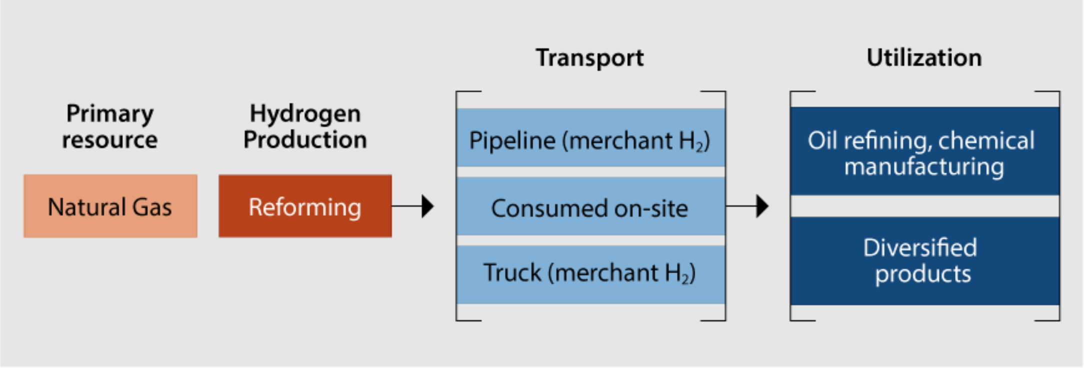
[48] IEA, *Global Hydrogen Review*, Paris, 2021, p. 74; J. Kurtz, S. Sprik, and G. Saur, et al., *On-Road Fuel Cell Electric Vehicles Evaluation: Overview*, National Renewable Energy Laboratory, NREL/TP-5400-73009, Golden, CO, March 2019, p. 12.

[49] An electrolyzer is an electrochemical device, powered by electricity, that decomposes water into hydrogen and oxygen.

refueling station provided sufficient transmission and distribution and power generation were available.

Figure 3. Large-Scale Production of Hydrogen from Natural Gas, Its Transport, and Use

Present-day conditions typical of Gulf of Mexico Coast or California

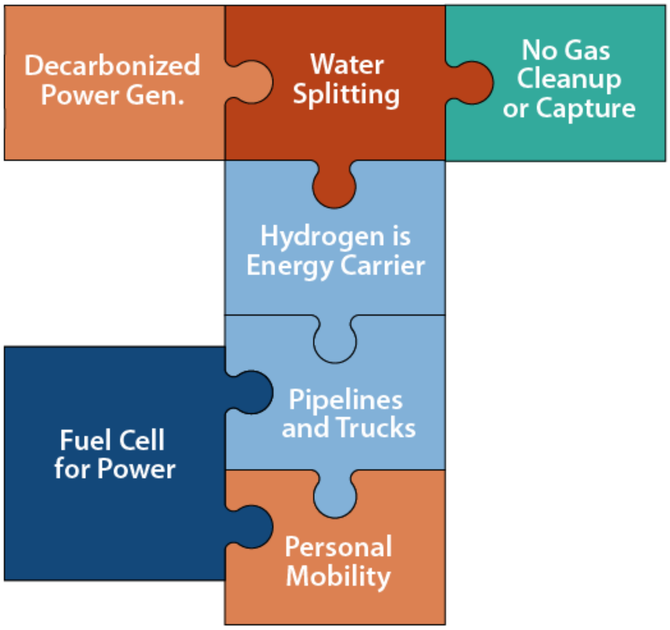


Source: CRS drawing. U.S. Department of Energy: Hydrogen and Fuel Cell Technologies Office, *Hydrogen Pipelines*, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

Notes: H_2 = hydrogen. Hydrogen production (reforming) can occur at refineries and chemical plants or at merchant hydrogen facilities. Color scheme is the same as in **Figure 2**.

Figure 4. Possible Future Green Hydrogen Energy Value Chain for Vehicles

Hydrogen made by large, centrally-located electrolyzers



Source: CRS.

Industry

Applications in industry use hydrogen for its chemical properties—as a reducing agent in steelmaking, for example. Many industrial processes also require external heat. Hydrogen could substitute for other fuels to provide this heat, potentially lowering quantities of pollutant gases.[50]

High-Temperature Heat

Hydrogen burns with characteristics favorable to providing high-temperature heat, with flame temperatures slightly above that of methane and with emissions of water vapor and potentially nitrogen oxides (NO_x).[51] Combustion of gases provides the heat for a number of industrial processes.[52] The value proposition for hydrogen is thus to provide this high-temperature heat, substituting for fossil fuels—the source of most high-temperature heat today.[53]

There was no dedicated generation of hydrogen for high-temperature heat as of 2019 globally.[54] A 2018 study by McKinsey found that, in four industry subsectors responsible for roughly half of industrial greenhouse gas (GHG) emissions—ethylene, ammonia, cement, and steel manufacture combined—roughly one-third of CO_2 emissions involve high-temperature heat (defined to be heat above 500°C in that study).[55]

Steelmaking

Steelmaking uses hydrogen as part of a mixture of gases produced from fossil fuels. Alternative, new, largely untried, methods of making steel might employ pure hydrogen. The rationale for using hydrogen in this way is to lower the emissions of the steelmaking process and to reduce environmental impacts.

The opportunity to substitute pure hydrogen lies mainly with a lesser-utilized process of primary steelmaking that is responsible for 7% of global primary steel production. This method begins by processing iron ore to make iron units that are further processed in an electric arc furnace (EAF).[56] In this method, the EAF is charged (i.e., fed) with so-called sponge iron, a type of direct reduced iron (DRI), and some scrap metal. **Figure 5** provides a conceptual diagram of the process. The DRI is made in a reactor from pre-processed iron ore. Three plants in the United States use direct reduction as of the end of 2021.[57]

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[50] Energy Transitions Commission, *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, Version 1.2, April 2021; Hydrogen Council, *Hydrogen Decarbonization Pathways: A Lifecycle Assessment*, January 2021; IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019.

[51] Combustion of hydrogen might necessitate use of NO_x reduction technologies. See U.S. EPA, Technology Transfer Network, *Nitrogen Oxides (NO_x): Why and How They Are Controlled*, https://www3.epa.gov/ttncatc1/cica/other7_e.html.

[52] These processes include, for example, melting, gasifying, drying, and mobilizing chemical reactions. IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 116.

[53] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 117.

[54] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 91.

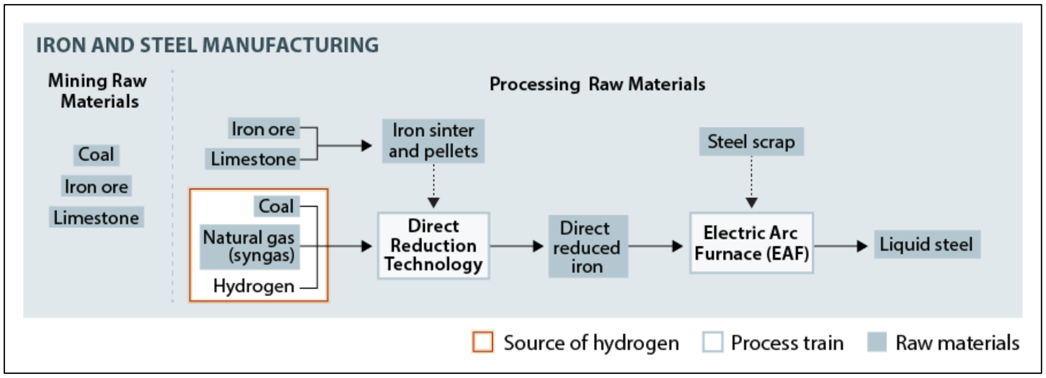
[55] Arnout de Pee, Dickon Pinner, and Occo Roelofsen, et al., *Decarbonization of Industrial Sectors: The Next Frontier*, McKinsey Sustainability, Amsterdam, The Netherlands, June 2018, p. 7, https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future.

[56] The EAF is also used in secondary steel production. In the United States these are sometimes known as mini-mills. The use of EAF for secondary steel production is far greater, globally, than its use in DRI-EAF steelmaking.

[57] MIDREX, *2021 World Direct Reduction Statistics*, Englewood Cliffs, NJ, September 2021,

The majority of DRI-EAF uses synthesis gas,[58] a mixture of carbon monoxide and hydrogen, to provide the chemical environment in the shaft furnace where DRI is made.[59] In India, coal-based DRI is predominant, in which coal is gasified, yielding carbon monoxide and hydrogen in addition to other gases.[60]

Figure 5. Direct Reduction of Iron



Source: CRS drawing adapted from CRS Report R47107, *Domestic Steel Manufacturing: Overview and Prospects*, by Christopher D. Watson.

Notes: The orange box shows the possibilities for generating hydrogen, whether from coal, natural gas (as synthesis gas or syngas), or pure hydrogen. Though not shown here, one type of direct reduced iron (DRI), hot briquetted iron, can be charged in a basic oxygen furnace to make steel rather than in an EAF. Liquid steel is later cast into semi-finished products. Hydrogen is not shaded as a raw material because it is not in commercial use as such.

At the demonstration level, projects are being designed to use pure hydrogen. The HYBRIT (HYdrogen Breakthrough Ironmaking Technology) project—funded by the European Union and the Swedish government and executed by several industrial concerns, universities, and other groups from civil society on a site in Sweden—will "intend to create a completely fossil-free value chain from mine to finished steel, with fossil-free pellets, fossil-free electricity and hydrogen."[61] The HYBRIT project envisages producing the hydrogen using electrolysis and storing the hydrogen underground as a buffer.

A second way of making primary steel can also use some pure hydrogen without substantially modifying the process train. Globally, approximately 90% of primary steel is made using the blast furnace to basic oxygen furnace (BF-BOF) route. The source of the chemical reducing agent in BF-BOF is generally the works arising gases (WAG) from coal. In a variant, hydrogen could be

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https://www.midrex.com/insight/world-dri-production-reaches-119-2-mt-in-2021/, pp. 12-14.

[58] Synthesis gas or syngas is principally a mixture of hydrogen and carbon monoxide. Syngas can also be produced by gasification of coal. The hydrogen produced in these mixtures could be deemed *direct hydrogen*, even though other gases are present, to indicate the hydrogen is produced for itself and not as a by-product in which another gas or product is of primary value.

[59] IEA, *Innovation Gaps, Industry, Iron & Steel: Gap 2. Direct Reduction Based on Hydrogen*, Paris, May 2019, https://www.iea.org/reports/innovation-gaps/industry. The gases create a chemically-reducing environment, hence the product is called direct *reduced* iron.

[60] Most DRI production in India uses coal, owing to relatively low coal prices. Institute for Industrial Productivity, *Industrial Efficiency Technology Database: Direct Reduced Iron*, http://www.iipinetwork.org/wp-content/Ietd/content/direct-reduced-iron.html.

[61] SSAB, LKAB, and Vattenfall, *Fossil-Free Steel—A Joint Opportunity!* https://www.hybritdevelopment.se/en/.

injected as an auxiliary reducing agent. At least one demonstration project is aimed at increasing the use of direct hydrogen in the BF-BOF process.[62]

The challenge of introducing and scaling-up the use of pure hydrogen in steelmaking is discussed later in the section "Costs and Drawbacks Affecting the Speed and Scale of Deployment."

Buildings—Thermal Comfort

Combustion of hydrogen in appliances can provide occupants of architectural spaces with thermal comfort, hygienic services (hot water and clothes drying), cooking services, and so forth. First, hydrogen gas could in principle be blended into natural gas transmission and distribution infrastructure for residential customers. Second, if a dedicated hydrogen pipeline system were to be in place, residential use of hydrogen would be part of a longer-term strategy for widespread use of hydrogen.

Combustion of natural gas provides heating to 61% of dwellings in North American markets, counting those where substantial demand for heating exists.[63] In the first step of the strategy above, hydrogen could be blended with natural gas and delivered in the existing pipeline network to its point of use; the end users would continue using the blended gas in appliances for energy services.

The International Energy Agency (IEA) estimates blending of between 5% and 20% hydrogen, by volume, would be possible.[64] Southern California Gas has successfully tested a 20% blend in a closed-loop system with residential appliances, and preliminary results showed such a blend was compatible with household natural gas appliances.[65] The hydrogen energy value chain (see **Figure 2**) would be as follows: primary resource—conversion to hydrogen—blending into natural gas pipeline—on-site combustion—thermal comfort. A technical limitation on the blending strategy has to do with the tendency of hydrogen to diffuse into the pipeline wall, valves, fittings, and welds. Effects such as cracking and blistering could lead to reduced service life or failure of the pipeline.[66] This risk of these effects is greater risk at the higher pressures characteristic of natural gas transmission pipelines than at the lower pressures of distribution lines.[67]

The blending option could be a transition stage because it may not require substantial new infrastructure, if the technical limitations do not prove prohibitive. The second, longer-term stage of the above strategy would require a dedicated hydrogen infrastructure for transmission and

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[62] The Japan Iron and Steel Foundation, *To the Future of the Low Carbon Blast Furnace: CO_2 Ultimate Reduction System for Cool Earth 50 (COURSE50) Project*, https://www.course50.com/en.

[63] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 146.

[64] Ibid., p. 144.

[65] Southern California Gas, "SoCalGas Among First in the Nation to Test Hydrogen Blending in Real-World Infrastructure and Appliances in Closed Loop System," press release, September 30, 2021, https://newsroom.socalgas.com/press-release/socalgas-among-first-in-the-nation-to-test-hydrogen-blending-in-real-world.

[66] See Peter Adam, et al., "Hydrogen Infrastructure—The Pillar of Energy Transition," white paper, Siemens Energy, September 15, 2020, pp. 14-15, https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf.

[67] See CRS Report R46700, *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, by Paul W. Parfomak.

delivery. The appliances themselves may also need to be adapted to the combustion of pure hydrogen.

A second way to lower emissions associated with the provision of thermal comfort in buildings is to use hydrogen fuel cells. This would require a source of pure hydrogen in the case of PEM fuel cells, with the consequence that the blended methane-hydrogen pipeline approach might not be compatible.[68] Once delivered on-site, the hydrogen would be consumed in the fuel cell and provide power to electric heating appliances or heat pumps.[69] The IEA believes that addressing heating in this manner would best be suited to large commercial buildings or campuses.[70]

Electric Power Sector—Balancing and Buffering

Hydrogen can balance supply of electricity with consumption of electricity and can *buffer* (i.e., store) electricity. Electric power system operators use various methods to keep supply and demand in balance. System operators curtail (i.e., reduce) electricity generation when there is not sufficient demand. Hydrogen offers the possibility of avoiding curtailment by serving as a ready source of demand; electrolyzers can convert the excess electricity supply into hydrogen via water electrolysis.[71]

The hydrogen generated could in principle be sold into merchant hydrogen markets, injected into natural gas transmission and delivery infrastructure, or marketed for other on-purpose uses of hydrogen.[72] A different value proposition is to use this hydrogen as a fuel to generate electricity on demand ("buffering"). The stored hydrogen accumulated during off-peak hours could be converted to electricity and dispatched when loads were highest. This arbitrage could combine with variable renewable energy (VRE) such as wind and solar power.[73] **Figure 6** shows the hydrogen energy value chain for such a concept.

As an energy storage medium, hydrogen is versatile and can be stored in small or large quantities for long periods of time.[74] Large-scale underground storage involves some use of energy to

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[68] Whether the fuel cell requires pure hydrogen would depend on its material complex. The fuel cell consists of several stacked layers of varied materials that support different stages of the electrochemical reaction and mass transport of the chemicals and gases. Fuel cells are categorized according to the type of material used in the electrolyte layer; for example, the PEM or "polymer electrolyte membrane" fuel cell, which reacts hydrogen with atmospheric oxygen. DOE, Hydrogen and Fuel Cell Technologies Office, *Parts of a Fuel Cell*, https://www.energy.gov/eere/fuelcells/parts-fuel-cell; DOE, Hydrogen and Fuel Cell Technologies Office, *Types of Fuel Cells*, https://www.energy.gov/eere/fuelcells/types-fuel-cells.

[69] The value chain would be as follows: primary resource—conversion to hydrogen—hydrogen pipeline—conversion to electricity by fuel cell—on-site electric heater or heat pump—thermal comfort.

[70] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 148.

[71] McKinsey Center for Future Mobility, *Hydrogen: The Next Wave for Electric Vehicles*, November 2017; IEA, *Technology Roadmap: Hydrogen and Fuel Cells*, Paris, 2015, p. 19.

[72] C. Baumann, R. Schuster, and A. Moser, "Economic Potential of Power-to-Gas Energy Storages," 10th International Conference on the European Energy Market (EEM), Stockholm, Sweden, May 2013, https://ieeexplore.ieee.org/document/6607315.

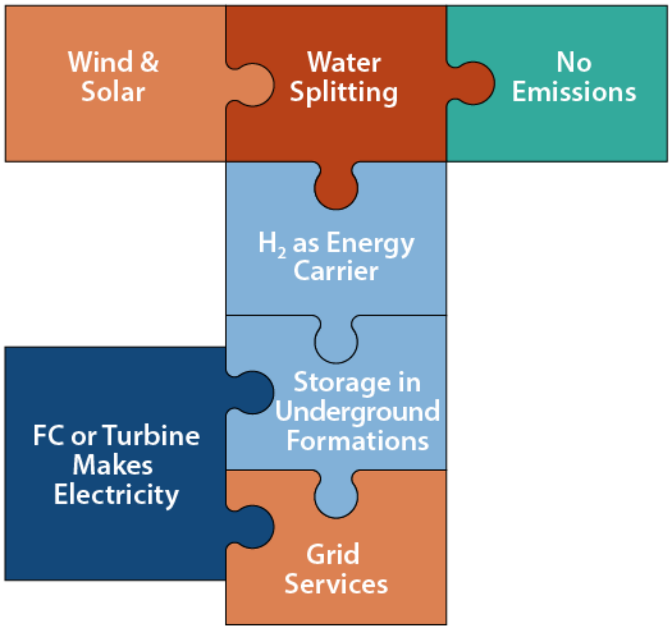
[73] F. Zenith, M. Nord Flote, and M. Santos-Mugica, et al., "Value of Green Hydrogen When Curtailed to Provide Grid Balancing Services," *Internatinal Journal of Hydrogen Energy*, vol. 47, no. 84, October 5, 2022, pp. 35541-35552; D. Ferrero, M. Gamba, and A. Lanzini, et al., "Power-to-Gas Hydrogen: Techno-Economic Assessment of Processes Towards a Multi-Purpose Energy Carrier," *Energy Procedia: 71st Conference of the Italian Thermal Machines Engineering Association*, vol. 101, 2016, pp. 50-57.

[74] Linde plc, *Power Buffering: Hydrogen's Role in Renewables*, https://www.lindehydrogen.com/applications/power-buffering.

compress the hydrogen and preserves roughly 90% to 95% of the energy of the hydrogen, net of energy used for compression.[75]

A DOE loan guarantee made in support of a large project on buffering is discussed below in the section "Recent Developments."

Figure 6. Buffering Using Hydrogen Storage



Source: CRS drawing.

Notes: Wind and solar power would have some emissions associated with manufacturing and site construction. FC = fuel cell.

Considerations for a Potential Hydrogen Economy

This section presents case studies of the value propositions just discussed for use of hydrogen.[76] Recent reports have highlighted three major considerations or criteria for a future hydrogen economy: environmental benefits, readiness for deployment, and cost-competitiveness.[77]

The first criterion considers the scope of the potential environmental benefits. Many multinational and international commitments and goals refer to a hydrogen economy and its potential in energy transitions. Examples of such commitments include the 2030 Climate Target Plan of the European Union; the U.S. goal of net-zero GHG by 2050; and the Paris Agreement.[78] A further

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[75] IEA, *Technology Roadmap: Hydrogen and Fuel Cells*, Paris, 2015, p. 19.

[76] The buffering value proposition for the electric power sector does not address all of these criteria.

[77] Energy Transitions Commission, *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, Version 1.2, April 2021; Hydrogen Council, *Hydrogen Decarbonization Pathways: A Lifecycle Assessment*, January 2021; IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019.

[78] European Commission, *EU Climate Target Plan 2030: Building a Modern, Sustainable and Resilient Europe*, September 2020, https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-

potential environmental benefit, also discussed below, might accrue due to substitution of hydrogen-based processes for incumbent processes that emit other pollutants.

The second criterion discussed in this section considers how ready the components are to enter widespread deployment. The third criterion considers the cost of hydrogen in different applications and compares these to the same application delivered instead with other combinations of fuels and technologies.

The use of hydrogen for residential and commercial heating and air conditioning (i.e., thermal comfort), in particular, is one of the end-use diversity requirements for the Regional Clean Hydrogen Hubs in the IIJA, discussed further below in "The IIJA and Funding for Hydrogen." Following these analyses is a discussion titled "Costs and Drawbacks Affecting the Speed and Scale of Deployment" for the hydrogen applications.

The discussion of these three criteria assumes that hydrogen end-use technologies deliver the same energy service as the incumbent technologies—for example, that FCEVs provide personal mobility with consumer attributes (e.g., acceleration, range) comparable to the ICEVs that dominate the fleet in the United States today. The analysis does not discuss what impact a shift in the mix of primary resources consumed might have on energy security—that is, whether such a shift would reduce the likelihood or severity of disruptions in the price or reliability of supply of a primary resource.

Potential Environmental Benefits and Drawbacks of a Hydrogen Economy

This section considers the criterion environmental benefits, and describes it relative to today's end-use technologies that deliver generally the same energy services. The applications described here involve a substitution strategy in which an application currently using fossil fuels switches over to using hydrogen. Quantitative findings are sensitive to the assumed values of leakage rates, conversion efficiencies, and other parameters. In addition, the findings are based on specific choices for how hydrogen is to be produced in a hydrogen economy, and some choices will result in higher emissions than others and could result in higher emissions than today's energy system.

The scope of the discussion in this section considers emissions of CO_2 during operation and, where such is not available, considers GHGs including CO_2 in the aggregate. Where appropriate the discussion considers emissions associated with the full hydrogen energy value chain, meaning the sequence of steps starting with conversion of the primary energy source into hydrogen and so forth as in the example of **Figure 4**.

The section does not consider non-emission impacts. For example, the life cycle environmental impacts of constructing and operating facilities are not analyzed, nor is the impact of salvage, recycling, and disposal of the vehicles or appliances that use the hydrogen or the conventional equipment that would be replaced.

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plan_en. U.S. Department of State and Executive Office of the President, The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, Washington, DC, November 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf; *Paris Agreement to the United Nations Framework Convention on Climate Change*, adopted by Conference of Parties No. 21, Decision 1/CP.21, U.N. Doc. FCCC/CP/2015/10/Add.1 December. 12, 2015, annex 1, http://unfccc.int/ resource/docs/2015/cop21/eng/10a01.pdf.

Transportation Sector—Personal Mobility

Hydrogen has been envisaged as a way to lower emissions from the transportation sector.[79] About 90% of U.S. transportation energy was consumed as petroleum fuels in 2021.[80] Passenger vehicles—cars, light trucks, and motorcycles—were responsible for 58% of U.S. transportation sector CO_2 emissions in 2019.[81] Such vehicles operate off-grid of any energy supply, such as the electric power grid, so that a fuel or other form of potential energy must be stored on board the vehicle.

Figure 7 shows the GHG emissions associated with one FCEV relative to a conventional gasoline vehicle from one life cycle analysis.[82] The figure shows, per mile driven, the CO_2-equivalent (CO_2-eq)[83] emissions summed along the entire hydrogen energy value chain up to the point of delivery to the vehicle. There are several bars because the calculations take account of the different ways of producing and transporting hydrogen, the different sources of the primary energy, and the physical state of the hydrogen. In the case of electrolysis of water, the fuel at the electric power plant is the primary energy. An important takeaway from the figure is the comparison to an ICEV of similar size and attributes.[84] The left-most bar shows the GHG from the oil—GHG that arise from extracting and refining the oil and delivering product to the refueling station—and the GHG from driving the car. On a percentage basis, per vehicle, a switch to hydrogen fuel used in FCEVs is estimated to save from 25% to over 85% compared with the current technology (gasoline ICEV). A similar study from the same laboratory, also comparing ICEVs to FCEVs, found on a well-to-wheels basis that carbon monoxide emission would be lower by 80% for the FCEV while NO_x emissions were not clearly better in one or the other type of vehicle.[85]

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[79] N.P. Brandon and Z. Kurban, "Clean Energy and the Hydrogen Economy," *Philosophical Transactions of the Royal Society A*, vol. 375, June 12, 2017; National Research Council and National Academy of Engineering, *The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs*, Washington, DC, 2004.

[80] S.C. Roberts and R.G. Boundy, *Transportation Energy Data Book: Edition 40—2022*, Oak Ridge National Laboratory, ORNL/TM-2022/2376, Oak Ridge, TN, June 2022, p. 2-7.

[81] Ibid., p. 12-10.

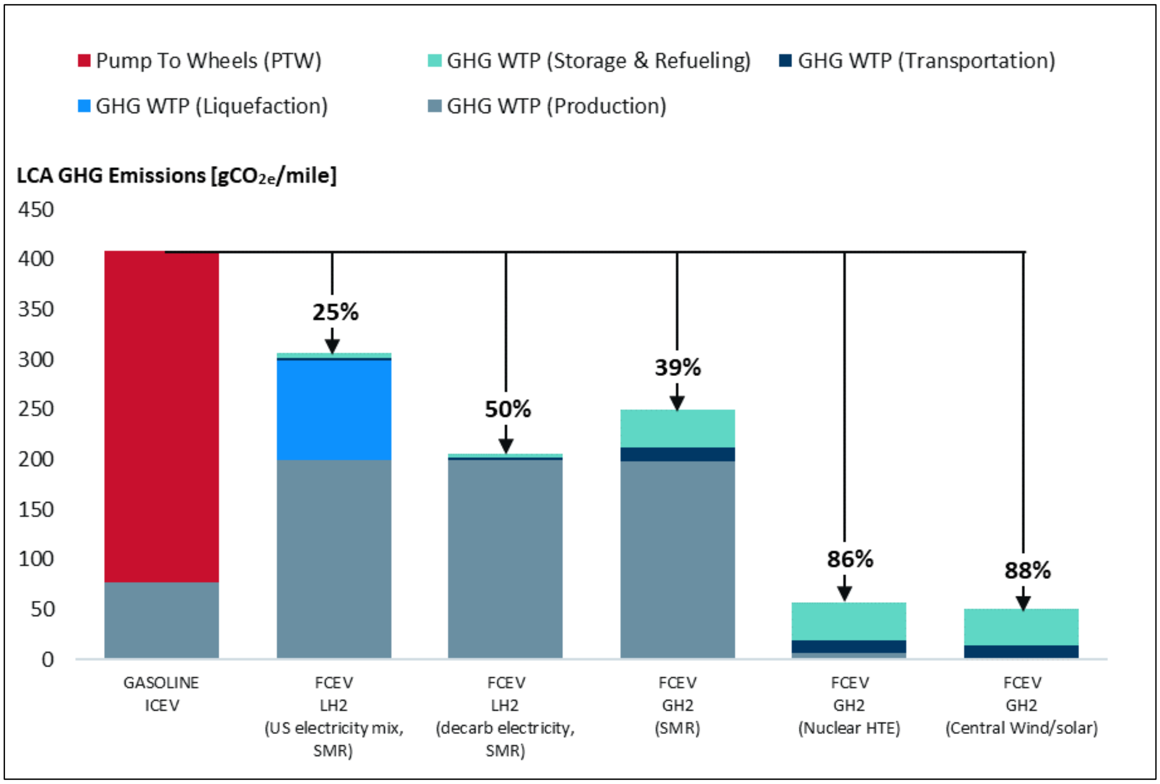
[82] Different life cycle analyses have different results in part due to the sensitivity of these results to the assumptions.

[83] CO_2-equivalent (CO_2-eq) is an index that converts the impact of diverse gases into one common unit so their impacts can be summed. The index used by Intergovernmental Panel on Climate Change and others is the global warming potential, which takes account of the physical phenomenon of radiative forcing of a gas integrated over a fixed number of years.

[84] The study assumed fuel economy as follows: 26 miles per gallon (MPG) for gasoline internal combustion engine vehicle and 55 MPG, gasoline equivalent, for the FCEV. Based on thermochemistry, one kilogram of hydrogen (lower heating value) and one gallon of gasoline (lower heating value) have roughly the same energy. The lower heating value (LHV) of enthalpy is a common measure of the energy available from combustion of a pure substance. The LHV does not include the latent heat when a substance changes from vapor to liquid phase. In contrast, the higher heating value (HHV) does and as a consequence is larger than, and not interchangeable with, LHV.

[85] X. Liu, K. Reddi, and A. Elgowainy, et al., "Comparison of Well-to-Wheels Energy Use and Emissions of a Hydrogen Fuel Cell Electric Vehicle Relative to a Conventional Gasoline-Powered Internal Combustion Engine Vehicle," *International Journal of Hydrogen Energy*, vol. 45, no. 1, January 1, 2020, pp. 972-983.

Figure 7. Greenhouse Gas Emissions Associated with Hydrogen Fuel by Different Means of Production (2019 technology)



Source: Adapted from data provided courtesy of Amgad Elgowainy based on Amgad Elgowainy, Jarod Kelly, and Qiang Dai, et al., *Life Cycle Analysis (LCA) of BEV and H2 FCEV with the GREET Model*, Argonne National Laboratory, presentation at the GREET Introduction Workshop, October 15, 2019.

Notes: Figure includes a comparison to an internal combustion engine vehicle (ICEV) on the far left. The ICEV has a bar segment of emissions from driving the vehicle (red bar—pump to wheels, or PTW). There is no corresponding bar segment for FCEVs as these are assumed to convert all the on-board fuel to water and not to other chemicals or gases. FCEV = fuel cell electric vehicle; GH2 = gaseous hydrogen; HTE = high-temperature electrolysis; LH2 = liquid hydrogen; SMR = steam methane reforming of natural gas; WTP = well-to-pump. The analysis assumed 26 miles per gallon (MPG) for the gasoline ICEV and 55 MPG, gasoline equivalent, for the FCEV. Words in parenthesis on the horizontal axis describe the electricity mix and/or hydrogen conversion methods assumed for the various means of production.

Industry

High-Temperature Heat

The environmental benefits of hydrogen in high-temperature heat applications would depend on how the hydrogen is produced. Two studies considered blue hydrogen (see text box, Hydrogen Production and "Hydrogen Colors") for provision of high-temperature heat. The first study estimates GHG emissions could be reduced by over 80% per-kilowatt-hour (kWh) of heat produced by 2030 if hydrogen were used in boilers and furnaces in place of the incumbent natural gas-fueled boilers and furnaces. The study considered hydrogen sourced from natural gas and produced by autothermal reforming[86] with a 98% rate of carbon capture.[87] A second study, considering CO_2 only and therefore not strictly comparable, noted that hydrogen produced with high rates of CO_2 capture (89%) could lead to a roughly 80% decrease in CO_2 emissions, were hydrogen substituted for the natural gas heat source.[88] The reduction in carbon emissions is, however, sensitive to the assumed rate of CO_2 capture, and at a lower rate of capture of 53% the two options—hydrogen and natural gas—hydrogen does not have a clear advantage. The largest reductions in CO_2 emissions are possible when hydrogen is produced by electrolysis powered by non-emitting sources of electricity as in so-called green hydrogen or in pink hydrogen (see text box).

Pure Hydrogen in Steelmaking

Steelmaking, as noted, uses hydrogen as part of a mixture of gases produced from fossil fuels. New and largely untried methods of making steel would use pure hydrogen and might be substituted into plants to lower emissions from the overall process. The HYBRIT project mentioned above, which is being designed to be free of fossil fuels, is one example of the interest in moving low- and zero-carbon methods further toward deployment.[89]

The DRI-EAF process, described above in "What Could a Hydrogen Economy Do?," could switch to using pure hydrogen as the chemical reducing agent (see **Figure 5**), whereas current DRI-EAF uses syngas. According to one study, using green hydrogen in a pure stream (i.e., not containing other gases) could lower emissions from the process by 60%. Using blue hydrogen and capturing large amounts of CO_2 could also achieve 60% reduction.[90] Both these figures assume the use of grid electricity to provide power for other steps in the process train, mainly to operate the EAF; the use of grid electricity incurs indirect GHG emissions. Switching to low-carbon electricity for those other steps would raise the overall emissions reduction rates above 80%.[91]

A second opportunity involves replacing retiring blast furnace steel plants (BF-BOF) with pure hydrogen-based DRI-EAF. At least one firm in Sweden has announced its intention to retire at least one BF-BOF plant and replace it with DRI-EAF.[92] According to one life-cycle assessment of such a replacement generically, this could result in 87% less CO_2 emitted per ton of steel.[93] An analysis by IEA estimated that, relative to BF-BOF, switching to DRI-EAF would result in roughly a one-quarter reduction in GHG (CO_2-eq) assuming today's technology and a grid-mix of

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[86] Autothermal reforming of natural gas utilizes steam and oxygen to produce hydrogen and, as its name suggests, provides its own source of heat from the chemical reaction itself without the need for external heat as in SMR.

[87] Hydrogen Council, *Hydrogen Decarbonization Pathways: A Lifecycle Assessment*, January 2021, p. 15.

[88] S.J. Friedmann, Z. Fan, and K. Tang, *Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today*, Columbia Center on Global Energy Policy, New York, NY, October 2019, p. 74, https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2_0.pdf.

[89] SSAB, LKAB and Vattenfall, *Fossil-Free Steel—A Joint Opportunity!* https://www.hybritdevelopment.se/en/.

[90] Z. Fan and J. Friedmann, *Low-Carbon Production of Iron & Steel: Technology Options, Economic Assessment, and Policy*, Supplemental Information, March 8, 2021, https://www.sciencedirect.com/science/article/pii/S2542435121000957#appsec2, Supplementary Material Figure S-3.

[91] Ibid., Figure S-3.

[92] SSAB AB, *Timeline for HYBRIT and Fossil-Free Steel: Timeline for Fossil-Free Steel Production*, https://www.ssab.com/en/company/sustainability/sustainable-operations/hybrit-phases.

[93] The analysis assumes hydrogen is produced using renewable electricity and that the electricity for the process is from the grid. Hydrogen Council, *Hydrogen Decarbonization Pathways: A Lifecycle Assessment*, January 2021, p. 20.

electricity representative of today's.[94] This includes emissions from electricity to generate the hydrogen and to operate the process train at the steel mill. The IEA analysis further considered the possibility of using non-emitting sources of electricity and projected that reductions greater than 90% of GHG would be possible assuming technology of year 2040.

A third opportunity would involve injection of hydrogen into the BF-BOF process as an auxiliary reducing agent. One paper estimates doing so would reduce CO_2 from the blast furnace by over 20% by decreasing the need for the reducing gas that arises from coal.[95]

Buildings—Thermal Comfort

Direct GHG emissions from combustion of fuel in buildings amounted to 6.4% of global GHG emissions from all sources in 2010.[96] Hydrogen combustion can reduce CO_2 emissions in proportion to the amount of natural gas it replaces; blending in green hydrogen at 5% to 20% by volume would reduce the GHG emissions of this application by 2% to 7%; the reduction in percentage is because the same volume of hydrogen at environmental conditions has lower energy than methane.[97] The hydrogen used in the appliance could slip unreacted past the point of combustion and contribute to point-source emissions. The value chain that delivers hydrogen to the building itself would likely have associated diffuse emissions. The contribution of hydrogen to global warming has not been established.

Technology Readiness

The criterion readiness for deployment will focus on technology readiness level (TRL). A hydrogen economy likely requires technologies that are sufficiently mature and can be manufactured in volume. **Figure 8** shows the readiness, as determined by the IEA,[98] of the critical pieces needed for the hydrogen applications discussed above in "What Could a Hydrogen Economy Do?" The TRL assessed for the different technologies and processes ranges from level 1 for the research and development (R&D) stage to level 9 for initial stages of commercialization to level 11 for economy-wide deployment, such as today's refinery-scale production of hydrogen. For the mobility application (i.e., LDVs), IEA assesses the fuel cell and the refueling stations at a high TRL—though neither is in widespread deployment. For industrial applications, steelmaking and high-temperature heat, the TRL is consistent with prototypes. For buildings, the TRL runs from level 6 for blending hydrogen into natural gas supply pipelines to level 9 for appliances that use hydrogen directly. For buffering and balancing electric power, the storage option is level 9,

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[94] IEA, *Achieving Net Zero Heavy Industry Sectors in G7 Members*, Paris, May 2022, p. 114.

[95] C. Yilmaz, J. Wendelstorf, and T. Turek, "Modeling and Simulation of Hydrogen Injection into a Blast Furnace to Reduce Carbon Dioxide Emissions," *Journal of Cleaner Production*, vol. 154, June 15, 2017.

[96] Intergovernmental Panel on Climate Change (IPCC), "AR5 Climate Change 2014: Mitigation of Climate Change," 2014, p. 6; Jørg Aarnes, Marcel Eijgelaar, and Erik A. Hekto, *Hydrogen as an Energy Carrier: An Evaluation of Emerging Hydrogen Value Chains*, DNV GL, Group Technology & Research—Position Paper 2018, Høvik, Norway, November 2018.

[97] Energy Transitions Commission, *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, Version 1.2, April 2021, p. 21.

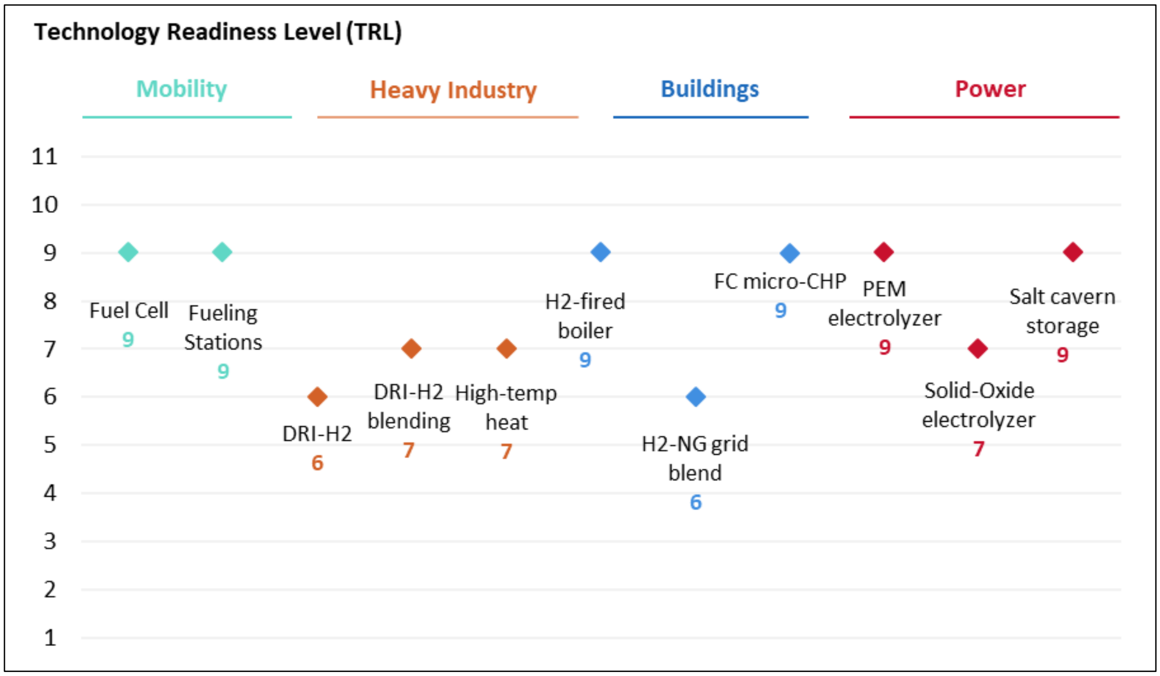
[98] For a description of the TRL system used by IEA, see IEA, *Energy Technology Perspectives 2020: Special Report on Clean Energy Innovation*, Paris, July 2020, pp. 67-68, https://www.oecd-ilibrary.org/energy/energy-technology-perspectives-2020_ab43a9a5-en.

while the electrolysis options are at level 7 (solid-oxide electrolyzer) or level 9 (PEM electrolyzer). Other analyses might assess these technologies at a different TRL.[99]

The different value propositions for hydrogen require different combinations of conversion, transmission, and end-use technologies. Elevating the TRL of one application might not enable other applications. So, for example, improved on-board vehicle storage would be beneficial for mobility but do little for industrial heat. Thus, the TRL levels depicted in **Figure 8** do not stand alone as indicators of the readiness of a hydrogen economy as a whole.

The hydrogen technologies depicted in **Figure 8**—for production, storage, and end-use—are at a high TRL level with the exception of steelmaking, which is still being prototyped or in the early stages of demonstration. Some technologies are at TRL 9 but not at the scale of deployment of today's industrial hydrogen as might be associated with a mature industry. To reach larger scale of deployment, the applications discussed in this report may need to overcome the challenges of mobilizing capital, faster permitting and regulatory approvals, and so forth. The following sections discuss further steps toward commercialization.

Figure 8. Technology Readiness of Hydrogen Applications Discussed in this Report



Source: Adapted from IEA, *ETP Clean Energy Technology Guide*, September 21, 2022, https://www.iea.org/articles/etp-clean-energy-technology-guide. High-temperature heat is described in International Energy Agency (IEA), *Global Hydrogen Review*, Paris, 2021, pp. 170-171.

Notes: TRL 5 is large prototype; 7 is pre-commercial demonstration; 9 is commercial. Levels 10 and 11 are deployment levels lying beyond initial market entry. See IEA, *Energy Technology Perspectives 2020: Special Report on Clean Energy Innovation*, Paris, July 2020, pp. 67-68, https://www.oecd-ilibrary.org/energy/energy-technology-perspectives-2020_ab43a9a5-en. CHP = combined heat and power; DRI = direct reduced iron; FC = fuel cell; H2 = pure hydrogen; PEM = polymer electrolyte membrane. DRI-H2 is pure, electrolyzer-produced hydrogen, which is at the prototype phase if used alone, but which can be blended with existing sources of hydrogen at a higher TRL depicted by "DRI-H2 blending."

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[99] See, for example S. Hossain, C.K. Saha, and M. Ismail, "Prospects and Challenges of Renewable Hydrogen Generation in Bangladesh," *International Journal of Hydrogen Energy*, in press; A. Boretti, "Technology Readiness Level of Solar Thermochemical Splitting Cycles," *ACS Energy Letters*, vol. 6, no. 4 (March 20, 2021), pp. 1170-1174.

Cost of Hydrogen Analyzed by Different Methods

The following subsections consider the criterion of cost-competitiveness of hydrogen versus today's fuels, and at what price hydrogen may become economic in the different applications. Hydrogen would have different costs depending on the supply chain needed to suit the application. Delivering and dispensing hydrogen into an FCEV would require additional infrastructure that might be priced into the delivered price, while captive use at a steel plant would have need for different infrastructure and thus potentially lower cost. The different applications in a hydrogen economy may become commercial at different times if economic forces alone determine their uptake. Currently, hydrogen fuel for most applications is not cost-competitive with the incumbent fuel. Current hydrogen costs at the pump are estimated in the $12-$13 per kilogram (kg) range, while, to be competitive with incumbent technologies, the cost of hydrogen would need to be in the range $3-$6/kg at the pump.

Willingness to Pay

One indication of how close hydrogen applications might be to reaching the market is the willingness to pay for it by would-be purchasers of hydrogen. Also described as the threshold price, this quantity is measured in dollars and represents the price at which the use of hydrogen would begin to displace other combinations of fuels and technologies. As demand for the application expands, more hydrogen would be delivered, and a market equilibrium would be reached at a lower price. DOE analyzed willingness to pay in its 2022 *Hydrogen Strategy and Roadmap* and other documents that made the following findings:[100]

- A 2020 DOE-sponsored study, referenced in the *Hydrogen Strategy and Roadmap*, shows no light-duty FCEVs in the reference case to 2050, which assumes the cost and performance of the *current* technology.[101] In scenarios involving technology breakthroughs or changes in resource and fuel prices, the DOE-sponsored study showed hydrogen for LDVs becoming competitive in year 2050 at a hydrogen price of $5.03/kg (2016 dollars).[102] DOE has estimated the current cost of dispensed hydrogen at $12-$13/kg (2016 dollars).[103] DOE also did not include LDVs as one of the transportation applications with significant near-term market potential in the 2022 *Hydrogen Strategy and Roadmap*.[104]

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[100] Prepared pursuant to Section 40314 of the Infrastructure Investment and Jobs Act (IIJA, P.L. 117-58). U.S. Department of Energy (DOE), *DOE National Clean Hydrogen Strategy and Roadmap (Draft—September 2022)*, September 2022.

[101] M.F. Ruth, P. Jadun, and N. Gilroy, et al., *The Technical and Economic Potential of the H2@Scale Concept Within the United States*, National Renewable Energy Laboratory, NREL/TP-6A20-77610, Golden, CO, October 2020, p. 58, https://www.nrel.gov/docs/fy21osti/77610.pdf.

[102] The analysis assumes a $2.20 city-gate cost as input to a vehicle choice model that represents "relevant attributes of technologies and consumer behavior such as technological learning by doing, range anxiety, access to recharging points, daily driving patterns, and willingness to accept technological innovation." Oak Ridge National Laboratory, *Introduction to MA^{3}T*, undated, https://teem.ornl.gov/ma3t.shtml. The cost of $5.03/kg includes the city-gate cost plus cost of delivery and dispensing plus taxes of $0.53/kg. M.F. Ruth, et al., op. cit., p. 58. Elsewhere, Elgowainy et al. give the $5.03/kg in 2015 dollars. A. Elgowainy, M. Mintz, and U. Lee, et al., *Assessment of Potential Future Demands for Hydrogen in the United States*, Argonne National Laboratory, ANL-20/35, Lemont, IL, October 2020, p. 49.

[103] N. Rustagi, A. Elgowainy, and J. Vickers, *Current Status of Hydrogen Delivery and Dispensing Costs and Pathways to Future Cost Reductions*, DOE, Record #18003, December 17, 2018, p. 1, https://www.hydrogen.energy.gov/pdfs/18003_current_status_hydrogen_delivery_dispensing_costs.pdf.

[104] Ibid.

- DOE's *Hydrogen Strategy and Roadmap* analyzed steelmaking and found that a hydrogen price of roughly $1.25/kg to $2.25/kg (2016 dollars) would be competitive.[105]
- DOE's *Hydrogen Strategy and Roadmap* estimated a threshold price for hydrogen of roughly $0.8/kg (2016 dollars) for industrial heat.[106] DOE assumed "20-50% of blending by volume for high-temperature end uses."[107]
- DOE's *Hydrogen Strategy and Roadmap* did not consider residential space heating.

DOE noted that its approach of considering only cost is conservative (i.e., will be less favorable to hydrogen) as there are features of hydrogen that cannot be monetized easily, including electric grid services and fuel flexibility.[108] DOE's analysis considered both conventional technologies and alternatives.

Explicit Comparison to Low-Carbon Alternatives

One study considered low-carbon alternatives that do not use hydrogen and used the estimated price of these alternatives as a threshold price. At the threshold price, hydrogen applications might begin to displace the low-carbon alternatives.[109] The low-carbon alternatives may use fuels and technology that differ from today's incumbent technologies. The study expressed costs in 2020 dollars as global averages unless otherwise noted.

- For LDVs, hydrogen would displace battery electric vehicles (BEVs), the deemed "low-carbon technology," at a dispensed hydrogen cost of between $3/kg and $4/kg. The study's authors did not conclude that small passenger vehicles within the LDV segment could achieve this.[110] For transportation overall, the study found that at a dispensed cost of $6/kg, hydrogen could meet 15% of energy demand by 2030. In this scenario, hydrogen would be satisfying the demand for rail, trucks, and long-range passenger vehicles.
- For steel production specific to China,[111] comparing hydrogen-based DRI steel to steel made with today's multi-gas mixtures, the threshold price was $1.90/kg. In a separate study, IEA estimated that hydrogen would increase the cost of steel made this way by 10% to 90%.[112]
- For steel made in Europe and Japan, a production cost of $1.80/kg to $2.30/kg would be lower than a blast furnace with carbon capture and storage (CCS)

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[105] DOE, *DOE National Clean Hydrogen Strategy and Roadmap (Draft—September 2022)*, September 2022, p. 28.

[106] DOE's estimate relied in part on *Hydrogen Council, Path to Hydrogen Competitiveness: A Cost Perspective*, January 2020, https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

[107] Email communication from DOE Office of Congressional and Intergovernmental Affairs, October 17, 2022.

[108] DOE, 2022, op. cit., p. 27.

[109] *Hydrogen Council, Path to Hydrogen Competitiveness: A Cost Perspective*, January 2020, https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf.

[110] Ibid., p. 16.

[111] Ibid.

[112] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 115.

having 90% capture (2030 technology status). The study estimated the $2.30/kg hydrogen price could be reached by 2030.[113]

- For industrial heat, hydrogen would not be competitive until its price declined to roughly $1.50/kg, assuming the incumbent technology is combustion heat with carbon capture and storage.[114]
- For space heating, the study found that hydrogen could displace one particular low-carbon option, heat pumps, at production cost of between $3/kg and $4/kg.

Costs and Drawbacks Affecting the Speed and Scale of Deployment

Implementing hydrogen applications would involve retrofitting existing hardware and facilities or building new ones. The different applications discussed in this report have varying requirements. Regulations and permitting may be necessary, including potentially those from multiple federal agencies.[115] Building new pipelines can require permits (see below, "Hydrogen Pipelines") and incurs regulatory oversight. Regulations, codes, and standards for the safe handling of hydrogen will likewise be important.[116]

For the personal mobility application discussed, FCEVs require a fuel and an infrastructure to deliver that fuel to a convenient dispensing point. The energy value chain shown in **Figure 4** shows one possible scenario: hydrogen made in large, centrally located electrolyzers. The build-out needed to support FCEVs could be large. The California Air Resources Board modeled a year-by-year build-out of hydrogen refueling stations and estimated that 1,000 refueling stations would be needed to support an envisaged 1 million light-duty FCEVs.[117] Honda, Hyundai, and Toyota have manufactured FCEV cars to buy or lease in North America. (Honda ended production of the Clarity Fuel Cell vehicle in 2021.[118]) There are currently over 50 public retail refueling stations, almost all of which are in California,[119] compared to roughly 145,000 gasoline stations nationwide. Carmakers had sold or leased nearly 15,000 light-duty FCEVs in the United States, cumulative through December 31, 2022,[120] with over 12,000 of these on the road at the end of 2021.[121] The sales of FCEV cars is small compared to cars of all fuel types sold in the

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[113] Ibid., p. 64.

[114] Ibid., p. 16.

[115] B. Ehrhart, A. Baird, A. Glover, et al., Sandia National Laboratories, *Overview of Federal Regulations for Hydrogen Technologies in the U.S.*, April 29, 2021, https://www.energy.gov/eere/fuelcells/articles/h2iq-hour-overview-federal-regulations-hydrogen-technologies-united-states.

[116] Nick Barilo, *The #H2IQ Hour: What's New with the Center for Hydrogen Safety?* DOE, Hydrogen and Fuel Cell Technologies Office, June 23, 2020, https://stage.energy.gov/sites/default/files/2020/07/f76/June 23 H2IQ What%27s New with the Center for Hydrogen Safety_compressed.pdf.

[117] California Fuel Cell Partnership, *The California Fuel Cell Revolution: A Vision for Advancing Economic, Social, and Environmental Priorities*, July 2018, p. 14, https://cafcp.org/sites/default/files/CAFCR.pdf.

[118] Honda, "Fuel Cell Technology Will Continue to Play a Role in Our EV Strategy," press release, June 16, 2021, https://hondanews.com/en-US/releases/release-53541be6030b25a47a2899aba12d4f66-fuel-cell-technology-will-continue-to-play-a-role-in-our-ev-strategy.

[119] DOE, Alternative Fuels Data Center, *Hydrogen Fueling Station Locations*, at https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY.

[120] California Fuel Cell Partnership, *By the Numbers: FCEV Sales, FCEB, and Hydrogen Station Data*, at https://cafcp.org/by_the_numbers.

[121] R.C. Samsun et al., "Deployment of Fuel Cell Vehicles and Hydrogen Refueling Station Infrastructure: A Global

United States, which comprised 3.4 million sales in 2020 alone; and even smaller relative to sales of all LDVs, including light trucks such as sport utility vehicles, which was 14.6 million in that year.[122] Overall, FCEV cars comprised slightly less than 1 in every 20,000 cars in the United States at the end of 2021.[123]

For industrial applications, the size, scope and scale of the transition to hydrogen would likely depend on whether a component or an entire system needs replacing. Changing out one step in the process train may be all that is necessary, such as might be the case for industrial heat. Converting other applications to hydrogen may require complete replacement of the plant. The frequency of such replacements may be slowed because large manufacturing lines can have economic lives of decades before such an opportunity arises.[124]

For steelmaking, there are two possibilities: replacing the blast furnace method (BF-BOF) with hydrogen-based DRI-EAF would be an example of complete replacement. The opportunity to make such replacements might be limited as the steel industry has been over capacity in recent years.[125]

The IEA estimates the other possibility—modifying existing DRI-EAF to use pure hydrogen—may incur a cost premium per tonne of steel produced of 10% to 90% versus natural gas-based hydrogen.[126] Much of the global steelmaking capacity is relatively new, which would suggest a low rate of stock turnover in the near term, making the corresponding opportunity to increase the use of DRI-EAF smaller unless relying heavily on retrofits.[127]

In the buildings applications discussed above, uncertainty about technical limitations has meant that demonstration projects blend small percentages of hydrogen due to the effect hydrogen is known to have on materials and the uncertainty about the suitability of hydrogen for use in appliances specified for natural gas, discussed earlier in "What Could a Hydrogen Economy Do?" in the discussion of buildings. Partly for this latter reason, one analysis rates the overall confidence as "low" for this application.[128]

A survey of hydrogen hubs currently operating or under development world-wide identified permitting as the number one policy barrier.[129] Respondents to the survey noted that local permitting authorities were not familiar with hydrogen. The survey included 28 stations—two in the United States, and the remainder in South America, Europe and Asia—that are either planning

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Overview and Perspectives," *Energies*, vol. 15, no. 4975, July 7, 2022, p. 5.

[122] S.C. Davis and R.G. Boundy, *Transportation Energy Data Book, Edition 39*, Oak Ridge National Laboratory, ORNL/TM-2020/1770, Oak Ridge, TN, April 2021, p. 3-9.

[123] Samsun et al., p. 23.

[124] A. Chalabyan, L. Mori, and S. Vercammen, *The Current Capacity Shake-Up in Steel and How the Industry Is Adapting*, McKinsey and Co.: Metals and Mining Practice, January 2018, p. 3, https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-current-capacity-shake-up-in-steel-and-how-the-industry-is-adapting.

[125] Ibid.

[126] IEA, *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, June 2019, p. 115.

[127] Much of the capacity in Asia is new relative to its expected life. IEA, *The Challenge of Reaching Zero Emissions in Heavy Industry*, Paris, September 19, 2020, https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry.

[128] Energy Transitions Commission, *Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy*, Version 1.2, April 2021, p. 17.

[129] Uwe Weichenhain, Markus Kaufmann, and Guillermo Matute Gomez, et al., *Hydrogen Valleys: Insights into the Emerging Hydrogen Economies Around the World*, Fuel Cells and Hydrogen 2 Joint Undertaking, Luxembourg, 2021.

(90%) or have implemented (10%) large scale, full hydrogen value-chain systems with multiple end-uses in a defined geography.

Recent Developments

The IIJA and Funding for Hydrogen

Congress enacted the IIJA in 2021, appropriating a total of $9.5 billion for explicit hydrogen programs. This included $8 billion for at least four Regional Clean Hydrogen Hubs.[130] DOE launched an initial funding opportunity announcement (FOA) in September 2022.[131] DOE plans to select six to ten Regional Clean Hydrogen Hubs for up to $6 to $7 billion, with a "preferred maximum" of $1.25 billion per hub. DOE states that the balance of the $8 billion may be reserved for additional hubs or other supporting activities. DOE is requiring a 50% cost share from non-federal sources and anticipates projects to be executed over a period of 8 to 12 years.[132] In issuing the FOA for hydrogen hubs, DOE said that full funding applications will be due by April 7, 2023.[133] In December 2022, DOE sent letters of encouragement to submit formal applications to 33 groups, based on concept papers those groups had submitted.[134] A total of 79 groups had submitted concept papers.

The IIJA appropriated an additional $1.5 billion for explicit hydrogen programs. This included $0.5 billion for the Clean Hydrogen Manufacturing Recycling Research, Development, and Demonstration Program. DOE has allocated these funds into two programs authorized by IIJA §40314 on manufacturing and recycling.[135] The IIJA appropriated $1 billion for the Clean Hydrogen Electrolysis Program.[136]

In addition to explicit hydrogen programs, the IIJA (§11401) authorized grants for charging and fueling infrastructure along designated alternative fuel corridors. Grantees may use the funds for a variety of alternative fuel infrastructure, including battery recharging or hydrogen fueling. The IIJA (§11101(b)(1)(C)) provides a total of approximately $2.5 billion for FY2022 to FY2026 from the Highway Trust Fund[137] for this new program.[138]

The IIJA enlarged the scope of the existing Advanced Technology Vehicle Manufacturing Loan Program to assist automakers in meeting fuel economy standards and to encourage domestic

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[130] The Regional Clean Hydrogen Hubs are discussed further in CRS Report R47289, *Hydrogen Hubs and Demonstrating the Hydrogen Energy Value Chain*, by Martin C. Offutt.

[131] DOE, *Bipartisan Infrastructure Law: Additional Clean Hydrogen Programs (Section 40314): Regional Clean Hydrogen Hubs Funding Opportunity Announcement*, DE-FOA-0002779, September 22, 2022, https://oced-exchange.energy.gov/FileContent.aspx?FileID=e159ff1f-5572-437e-b02d-b68acb461893.

[132] Ibid., p. 17.

[133] DOE, "Biden-Harris Administration Announces Historic $7 Billion Funding Opportunity to Jump-Start America's Clean Hydrogen Economy," press release, September 22, 2022, https://www.energy.gov/articles/biden-harris-administration-announces-historic-7-billion-funding-opportunity-jump-start.

[134] David Iaconangelo, "DOE Eyes Winners for Nation's First Hydrogen Hubs," *Energy Wire*, January 3, 2023.

[135] The two programs are authorized in §815a and b of the Energy Policy Act of 2005 (EPACT, P.L. 109-58).

[136] For further discussion, see CRS In Focus IF12163, *Department of Energy Funding for Hydrogen and Fuel Cell Technology Programs FY2022*, by Martin C. Offutt.

[137] For a description of the Highway Trust Fund, see CRS Report R47022, *Federal Highway Programs: In Brief*, by Robert S. Kirk.

[138] CRS Report R47034, *Energy and Minerals Provisions in the Infrastructure Investment and Jobs Act (P.L. 117-58)*, coordinated by Brent D. Yacobucci, p. 4. See "Division A—Surface Transportation," prepared by Melissa N. Diaz.

production of more fuel-efficient vehicles.[139] DOE has not made such loans for purposes of manufacturing hydrogen FCEVs.[140] The IIJA (§40401) enlarged the scope to cover qualifying MHD vehicles, and the Consolidated Appropriations Act, 2023 (P.L. 117-328), Division D, Section 308, repealed the restrictions from IIJA §40401(a)(2) that would have otherwise prevented the use of prior appropriations for this purpose.

Demonstration Projects

DOE approved a loan guarantee in June 2022 for a project to generate hydrogen and store it underground.[141] The guarantee was for a $504 million loan[142] to construct 220 megawatts (MW) of electrolyzers in Delta, UT, paired with underground storage caverns to store the hydrogen. The estimated storage capacity in each of two caverns is 5.5 million kg of hydrogen. Each cavern would have roughly 110 gigawatt-hours (GWh) of stored potential energy, assuming a combined-cycle gas turbine were used to re-electrify the hydrogen.[143] The project is to utilize the buffering strategy discussed earlier. The off-taker (i.e., user) for the stored hydrogen plans to use a hydrogen-capable gas turbine supplied by project partner Mitsubishi Power Americas to generate electricity.[144] The project, known as Advanced Clean Energy Storage, planned to be at the site of the current Intermountain Power Project, originally a coal-fired power plant, which sells electricity to the Los Angeles Department of Water and Power.[145] **Figure 6** shows the hydrogen energy value chain that is generally the same as the project's.

Legislative Activity

Since the start of the 116th Congress, Congress has proposed and enacted hydrogen-related legislation addressing federal research, development, and demonstration activities and funding; medium- and heavy-duty vehicles[146] (MHD vehicles, i.e., trucks); and pipelines. More than 80 bills were introduced in the 117th Congress related to hydrogen energy or fuel cells. Some of these bills, or provisions thereof, were enacted as part of the IIJA (P.L. 117-58). Potential implementation and oversight issues related to these provisions might be of interest in the 118th Congress. At least five bills addressing hydrogen energy or fuel cells have been introduced in the 118th Congress. At least five additional bills were directed generally at other topics and mention hydrogen in the 118th Congress.

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[139] CRS Report R42566, *Alternative Fuel and Advanced Vehicle Technology Incentives: A Summary of Federal Programs*, by Lynn J. Cunningham et al.

[140] Email communication from DOE Office of Congressional and Intergovernmental Affairs, July 6, 2022.

[141] DOE, *DOE Announces First Loan Guarantee for a Clean Energy Project in Nearly a Decade*, June 8, 2022, at https://www.energy.gov/articles/doe-announces-first-loan-guarantee-clean-energy-project-nearly-decade.

[142] Title XVII of the Energy Policy Act of 2005, P.L. 109-58, authorizes DOE to issue loan guarantees.

[143] Email communication from Mitsubishi Power, January 27, 2023.

[144] Mitsubishi Power Americas, "World's Largest Renewable Energy Storage Project Announced in Utah," press release, May 30, 2019, at https://power.mhi.com/regions/amer/news/190530.html.

[145] Intermountain Power Authority, *IPP Renewed*, https://www.ipautah.com/ipp-renewed/.

[146] Medium- and heavy-duty vehicles range in gross weight from 10,000 lbs., including payload, corresponding to certain trucks and vans, and on up to 80,000 lbs. for concrete mixers, articulated combination tractor-trailers, and other large vehicles.

Issues for Congress

This section discusses potential policy options related to accelerating the scale-up of the hydrogen economy, if such a goal were to be pursued. In the process of scaling up, a hydrogen economy might address other policy objectives, and this section does not explicitly evaluate these, which include environmental externalities, safety, jobs and economic growth, and access to affordable and reliable supplies of energy.

Incentives for Private Sector Investment

Current federal hydrogen projects and programs—including R&D, loan guarantees, development of codes and standards, and so forth—are intended to lead to increased private-sector investment in hydrogen technologies. The Regional Clean Hydrogen Hubs created in IIJA are to provide insights and validate some of the claimed benefits (environmental and otherwise) of the hydrogen economy and identify technology needs.[147] Additionally, new tax incentives for the production of clean hydrogen were introduced in P.L. 117-169, commonly referred to as the Inflation Reduction Act of 2022. These and other tax incentives are described in the text box below. As of June 2022, DOE had $2.5 billion in remaining loan guarantee authority in its Innovative Clean Energy program, which provided the loan guarantee for the Advanced Energy Storage Project in Delta, UT, in June 2022, discussed earlier.[148] These existing programs and activities could be the subject of congressional oversight.

The oversight of the Regional Clean Hydrogen Hubs might take note of the criteria for the selection of the hydrogen hubs specified in the IIJA (§40314). The feedstock diversity criterion in the IIJA calls for at least one hub each based on fossil fuels, renewable energy, and nuclear energy. The end-use diversity criterion specifies at least one hub each to be based on electric power generation; transportation sector; industrial sector; and commercial and residential heating. All criteria apply "to the maximum extent practicable." The geographic diversity criterion requires that, collectively, the hubs shall be located in a different region of the United States and shall use energy resources that are abundant in that region. At least two hubs "shall be located in the regions of the United States with the greatest natural gas resources." In addition, the IIJA instructs the Secretary of Energy to "give priority to regional clean hydrogen hubs that are likely to create opportunities for skilled training and long-term employment to the greatest number of residents of the region."

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[147] Testimony of Sunita Satyapal, Director, Hydrogen and Fuel Cell Technologies Office, DOE, during U.S. Congress, Senate Energy and Natural Resources, *Clean Hydrogen*, 117th Cong., 2nd sess., February 10, 2022.

[148] DOE, *DOE Announces First Loan Guarantee for a Clean Energy Project in Nearly a Decade*, June 8, 2022, at https://www.energy.gov/articles/doe-announces-first-loan-guarantee-clean-energy-project-nearly-decade.

Tax Incentives for Hydrogen in the Inflation Reduction Act[149]

P.L. 117-169, commonly referred to as the Inflation Reduction Act of 2022, created a new tax credit for the production of clean hydrogen and expanded and extended existing tax credits supporting the use of fuel cells and fuel cell vehicles.

Tax Credit for the Production of Clean Hydrogen

Starting in 2023, new clean hydrogen production facilities, or facilities modified to produce clean hydrogen, may be able to claim a tax credit for each kilogram (kg) of qualifying hydrogen produced during the first 10 years of operation.[150] Tax credits of up to $3 per kg can be claimed for hydrogen achieving a lifecycle GHG emissions rate of less than 0.45 kg of carbon dioxide equivalent (CO_2-eq) per kg produced at facilities paying prevailing wages and meeting registered apprenticeship requirements. Hydrogen having a lifecycle GHG emissions rate of less than 4 kgs of CO_2-eq, but not achieving the 0.45 kg threshold, might qualify for tax credits at a reduced amount. Facilities producing clean hydrogen that do not pay prevailing wages or meet registered apprenticeship requirements may also claim credits, but the credit amount is one-fifth of the credit amount otherwise available. Tax-exempt facilities may be able to receive the credit as direct pay, allowing the non-taxpaying entities access to the federal financial incentive. Taxpayers may elect to receive the tax credit as direct pay, in certain circumstances. A facility must commence construction by December 31, 2032, to be eligible for the clean hydrogen production credit. The new tax credit for the production of clean hydrogen is estimated to reduce federal tax revenues by $13.2 billion from FY2022-FY2031. Of that total, $5.3 billion is expected to be outlays for direct payments.[151]

Tax Credits for Fuel Cells[152]

Through 2024, a 30% investment tax credit (ITC) can be claimed for qualifying business investments in fuel cell power plants if the project pays prevailing wages and meets registered apprenticeship requirements (a 6% ITC is available for projects that do not meet the wage and apprenticeship requirements).[153] The credit for fuel cell property is limited to $1,500 for each 0.5 kilowatt of capacity of the property. After 2024, taxpayers investing in zero-emissions electric power generation facilities, including fuel cell power plants, may be able to claim a 30% ITC (again, a 6% credit is available for facilities that do not pay prevailing wages or meet registered apprenticeship requirements).[154] For these ITCs, the tax credit amount is increased for investments made in energy communities or for investments meeting certain domestic content requirements. Tax-exempt entities may be able to receive the ITCs as direct pay.

Individual taxpayers may also be able to claim tax credits for fuel cell power plants installed at their primary residence.[155] For residential property, the credit is limited to $500 for each 0.5 kilowatt of capacity. The tax credit is 30% through 2032, scheduled to phase down to 26% in 2033, 22% in 2034, and expire after 2034.

Taxpayers making investments to establish, expand, or re-equip a fuel cell manufacturing facility might also apply for allocations of the advanced energy manufacturing tax credit.[156] Taxpayers selected for allocations are to be able to claim a 30% tax credit for projects that pay prevailing wages and meet registered apprenticeship requirements (the credit is limited to 6% for projects that do not pay prevailing wages or satisfy registered apprenticeship requirements). Taxpayers may also apply for allocations of the advanced energy manufacturing tax credit for investments in fuel cell vehicle or fuel cell vehicle-infrastructure manufacturing facilities.

Tax Credits for Fuel Cell Vehicles and Fuel Cell Vehicle Infrastructure[157]

Tax credits may be available for the purchase of fuel cell vehicles, including new fuel cell vehicles assembled in North America, used vehicles purchased by individuals, and commercial fuel cell vehicles.[158] These vehicle-related credits expire December 31, 2032. Both business and individual taxpayers may also be able to claim tax credits for investments in hydrogen refueling infrastructure investments.[159]

Regulation

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[149] For additional information, see CRS Report R47202, *Tax Provisions in the Inflation Reduction Act of 2022 (H.R. 5376)*, coordinated by Molly F. Sherlock.

Hydrogen Pipelines

DOE's 2020 *Hydrogen Program Plan* identified rights-of-way and permitting for hydrogen pipelines as being among the needs and challenges to overcome for hydrogen delivery infrastructure.[160] Some of the policy issues that Congress could examine include the regulation of pipeline siting, including potential federal-state jurisdictional conflicts, and the regulation of pipeline rates and terms of service.[161] For example, some hydrogen proponents have suggested that Congress could establish federal siting authority for interstate hydrogen pipelines analogous to the Federal Energy Regulatory Commission's (FERC's) natural gas siting authority under the Natural Gas Act.[162] There are a number of additional factors that might determine whether any project to site, permit, and construct a pipeline is completed.[163]

Author Information

Martin C. Offutt
Analyst in Energy Policy

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[150] 26 U.S.C. §45V.

[151] Joint Committee on Taxation, Estimated Budget Effects of the Revenue Provisions of Title I—Committee on Finance, of an Amendment in the Nature of a Substitute to H.R. 5376, "An Act to Provide for Reconciliation Pursuant to Title II of S.Con.Res. 14," as Passed by the Senate on August 7, 2022, and Scheduled for Consideration by the House of Representatives on August 12, 2022, JCX-18-22, Washington, DC, April 9, 2022, https://www.jct.gov/publications/2022/jcx-18-22/.

[152] The Joint Committee on Taxation (JCT) did not provide cost estimates for the ITC, clean electricity ITC, residential energy efficient property credit, or the advanced energy manufacturing credit by type of qualifying technology. Thus, no cost estimates are provided for these provisions.

[153] 26 U.S.C. §48.

[154] 26 U.S.C. §48E.

[155] 26 U.S.C. §25D.

[156] 26 U.S.C. §48C.

[157] The Joint Committee on Taxation (JCT) did not provide cost estimates of tax credits for fuel cell vehicles or fuel cell vehicle infrastructure separate from the estimates for other clean vehicles (including plug-in electric vehicles). Thus, no cost estimates are provided for these provisions.

[158] 26 U.S.C. §§ 30D, 25E, and 45W. For more information, see CRS Insight IN11996, *Clean Vehicle Tax Credits in the Inflation Reduction Act of 2022*, by Molly F. Sherlock.

[159] 26 U.S.C. §30C.

[160] DOE, *Hydrogen Program Plan*, DOE/EE-2128, Washington, DC, November 2020, p. 6.

[161] Currently, regulation of hydrogen pipeline siting, commercial service, security, and safety is divided among federal agencies and the states. Federal jurisdiction resides variously with the Surface Transportation Board (STB), the Federal Energy Regulatory Commission (FERC), the Transportation Security Administration (TSA), and the Pipeline and Hazardous Materials Safety Administration (PHMSA) within the Department of Transportation (DOT). CRS Report R46700, *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, by Paul W. Parfomak.

[162] James Bowe and William Rice, "Building the Hydrogen Sector Will Require New Laws, Regs," Law360, January 13, 2021.

[163] CRS Report R46700, *Pipeline Transportation of Hydrogen: Regulation, Research, and Policy*, by Paul W. Parfomak.

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