Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation

State Energy Policy, Program, and Planning Considerations

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Contents

DISCLAIMER

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Abstract

Hydrogen offers potential pathways for decarbonizing the electricity system, hard-to-electrify industrial and heating applications, and heavy transportation. It can provide large-scale and long-duration energy storage to balance variable power generation and demand. Hydrogen offers non-carbon paths as both energy and material input for ammonia, steel, fuels, and other production. It can be made from non-carbon renewable and nuclear generation as well as from fossil fuel sources that can be coupled with carbon capture, utilization, and storage (CCUS). There are economic development opportunities for new technologies, processes, and applications as well as to leverage and adapt some existing natural gas, petroleum, and petrochemical infrastructure and expertise for hydrogen-based energy and production. Research, development, and demonstration (RD&D), environmental policies, economies of scale and scope, economic development programs, and other measures will affect hydrogen's path. State Energy Offices and other pertinent agencies should consider hydrogen options and opportunities, including supportive policy, program, and regulatory measures, in developing their energy, environmental, and economic development plans.

Overview - Hydrogen Types, Production, and Uses

Hydrogen (H_2), a simple molecule made of the lightest element, offers pathways to a clean energy system and climate-friendly industrial processes. State Energy Officials may wish to consider the potential and opportunities for hydrogen in their states' energy, environmental, and economic development policies and planning.

The United States has an established industrial base that makes about 10 million metric tons per year of hydrogen primarily for use in petroleum refining and ammonia production, with small amounts for other processes.[1] However, its potential applications are manifold, including:

- providing large scale and long-term energy storage to enhance the electricity system and better utilize renewable and nuclear generation,
- decarbonizing various chemical, metal, and material production processes,
- leveraging fossil fuel-based resources, infrastructure, workforce, and expertise for cleaner energy and industrial applications, and
- powering transportation, including heavy duty trucking, rail, marine, and even aviation modes.[2]

Today, industry makes hydrogen almost completely from methane (CH_4) in natural gas, mostly through steam methane reforming (SMR), releasing carbon dioxide (CO_2) in the process.[3] Coal, oil, biomass, and carbon-containing wastes can also be hydrogen sources. Coupled with carbon capture, utilization, and storage (CCUS), these sources can, in principle, be made zero- or even net negative-carbon emissions.[4]

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[1] Elgowainy, A., et al., Assessment of Potential Future Demands for Hydrogen in the United States (2020)

[2] While most analyses focus on heavy duty transportation, there are also efforts to commercialize hydrogen fuel cell light-duty vehicles in competition with electric vehicles; see California Fuel Cell Partnership https://cafcp.org/ and S. C. Kang "Japan Keeps Auto Industry's Hydrogen Dreams Alive" https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/japan-keeps-auto-industry-s-hydrogen-dreams-alive-62160857 . Also, see U.S. DOE, "Fact of the Month November 2018: There Are Now More Than 20,000 Hydrogen Cell Forklifts in Use Across the United States" for an interesting niche application, https://www.energy.gov/eere/fuelcells/fact-month-november-2018-there-are-now-more-20000-hydrogen-fuel-cell-forklifts-use

[3] U.S. Department of Energy, "Hydrogen Production: Natural Gas Reforming," https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming In addition to SMR, a partial oxidation process is also available. In China, coal is often the feedstock for making hydrogen.

[4] NASEO provides additional information and resources on CCUS at https://www.naseo.org/issues/energy-environment-climate/ccus.

However, “green” electrolytic hydrogen—using electricity from zero-carbon generation to split water (H_2O) into hydrogen and oxygen (O_2)—offers perhaps the largest long-term opportunity.[5] A palette of “colors” has emerged as shorthand to denote varied hydrogen sources and production processes (Table 1). The color categories are not fixed, with different groups offering varied definitions; and the colors can run together as new sources and processes are considered, such as hydrogen produced from biomass, plastic wastes, or blends of natural gas and biogases.

TABLE 1. SOURCES OR “COLORS” OF HYDROGEN*

“Color”	Hydrogen production source and process
Green	**Electrolytically from near zero-carbon* generation (renewable, nuclear**)**
Turquoise	**Pyrolytically from methane with solid carbon byproduct*** **
Blue	**From fossil fuel with CCUS**
Gray	**From natural gas using SMR without CCUS******
Brown	**From gasified coal without CCUS**
No color	**Electrolytically from grid-average generation (emission rates vary by place and time)**

* All sources have some upstream emissions associated and emit some carbon during their life cycle.
** Some add “red” for nuclear-generated electrolytic hydrogen and “white” for biomass-derived hydrogen.[6]
*** Still in research and development (R&D).
**** Can include partial oxidation process as well as SMR.

While furnaces, engines, fuel cells, and chemical reactors are Indifferent to the provenance of hydrogen molecules, the sources and processes do matter for practical application. For example, electrolytic hydrogen may be a way to store excess solar, wind, and off-peak nuclear and hydro generation—at larger scale and for longer periods (days to seasonally) than may be practical for batteries—for use during periods of high demand and low renewable generation (when it is less or not sunny or windy). (See Box 1, American Power Sector Hydrogen Projects.*)*

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[5] Research is also underway on thermal and photoelectrochemical processes to split water to make hydrogen.

[6] Schnegelberger, J., “Exploring Hydrogen’s Role in the Energy Economy” in Hydrogen—A Renewable Reliability Gap Solution (POWER Magazine webinar May 5, 2021) https://www.bigmarker.com/powermag-events/Hydrogen-A-Renewable-Reliability-Gap-Solution-814e065d3670b543d91de0f8?utm_bmcr_source=web-listing

BOX 1. AMERICAN POWER SECTOR HYDROGEN PROJECTS

Hydrogen can support the nation's power sector transition to net-zero emissions by:

- building on combustion- and thermal-based engineering expertise,
- augmenting and extending the value of renewable generation,
- complementing battery and other energy storage, and
- advancing new generation approaches like fuel cell technologies to deliver clean, reliable, and economic energy.

Several American projects are leading the way toward employing hydrogen in complement to renewable power generation to help green the electricity sector.

The Intermountain Power Project (IPP) currently provides coal-fueled electricity to municipal and cooperative electric utilities across six Western states.[7] A new IPP Renewed project, owned by the Intermountain Power Agency (IPA) and managed by IPP's largest customer, the Los Angeles Department of Water and Power (LADWP), will retire existing coal-fueled units near Delta, Utah by 2025. They will be replaced by natural gas-fueled units capable of blending in hydrogen to produce 840 megawatts (MW) of net electrical output. The project will build hydrogen production and storage facilities, leveraging its fortuitous location over a geologic salt dome suitable for hydrogen storage. Also, electricity transmission links to Southern California will be upgraded. The project will enable excess renewable power generation, such as daytime solar generation in California, to be stored as hydrogen in large amounts for long periods, including seasonally, to provide power during periods of low renewable generation. The new generation units will initially burn a blend of natural gas and hydrogen, with plans to transition to 100 percent green hydrogen by 2045.

Project construction is expected to employ about 800 workers, to peak in 2023, while preserving plant jobs and tax base that would otherwise be lost with the coal units' retirement. IPP Renewed may also stimulate additional economic development by establishing a hydrogen hub that creates opportunities in such areas as transportation and chemical and steel production.

In Florida, NextEra Energy's Florida Power and Light intends to pilot blending green hydrogen generated from otherwise curtailed solar power with natural gas at its Okeechobee combined cycle power plant as a step, along with other renewable and battery storage investments, toward diversifying and enhancing the resilience of its generation while lowering its greenhouse gas footprint.[8] San Diego Gas and Electric indicated plans for developing green hydrogen storage.[9] In Hannibal, Ohio, Long Ridge Energy Terminal, with New Fortress Energy and GE, is converting an existing 485 MW combined cycle power plant to run on a blend of hydrogen byproduct from nearby industry with natural gas.[10] The project partners plan over time to transition the facility to be fueled by 100 percent green hydrogen and possibly take advantage of nearby salt formations for hydrogen storage.

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[7] IPP Renewed, https://www.ipautah.com/ipp-renewed/

[8] Pearl, L., 2021, "NextEra sees hydrogen as key to deep decarbonization, takes small steps for now," Utility Dive (April 22, 2021) https://www.utilitydive.com/news/nextera-sees-hydrogen-as-key-to-deep-decarbonization-takes-small-steps-for/598855/

[9] Ibid.

[10] Long Ridge Energy Terminal, "Long Ridge Energy Terminal Partners with New Fortress Energy and GE to Transition Power Plant to Zero-Carbon Hydrogen," https://www.longridgeenergy.com/news/2020-10-13-long-ridge-energy-terminal-partners-with-new-fortress-energy-and-ge-to-transition-power-plant-to-zero-carbon-hydrogen

In another example, states and regions with a concentration of petrochemical and related industries, heavy transport demand (e.g., ports), and, perhaps, CCUS-suitable geology may map a hydrogen development path utilizing fossil and renewable resources that leverage existing industrial expertise and infrastructure. (See Box 2, U.S. Gulf Coast.)

BOX 2. THE U.S. GULF COAST

The U.S. Gulf Coast is a major center for the current hydrogen industry, serving the region's many petroleum refineries and petrochemical facilities. Air Products reportedly operates the world's largest hydrogen network on the Gulf Coast, extending from the Houston Ship Channel to New Orleans, Louisiana. The network includes 600 miles of pipeline and 22 production facilities providing 1.4 billion standard cubic feet of hydrogen per day to customers.[11] Praxair's Gulf Coast hydrogen operations includes about 300 miles of pipeline from Freeport, Texas to Lake Charles, Louisiana and includes the industry's first and (so far) only commercial hydrogen storage cavern.[12]

The Gulf region's hydrogen production is largely gray, from natural gas using SMR. Some has a blue tinge, such as that produced since 2013 by Air Products at its Port Arthur, Texas plant which mitigates 5 million metric tons of CO_2 annually through carbon capture and storage.[13] The region's old oil and gas fields are well suited for carbon sequestration while its salt domes and, perhaps, old gas fields can provide hydrogen storage. Also, increasing wind and solar generation in Texas offers green hydrogen opportunities for storing excess renewable generation as well as for supplying industry and transportation with renewably derived feedstock and fuel.

The rich confluence of industrial facilities, infrastructure, and expertise in fuels, chemical processing, power production, and transportation and logistics, along with favorable geology, offers the Gulf Coast an economic development path toward a net-zero carbon emission future.

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[11] "Air Products' Texas Plant Adds Hydrogen Supply to Guld Coast Pipeline Network," Gas Processing & LNG, http://www.gasprocessingnews.com/news/air-products%E2%80%99-texas-plant-adds-hydrogen-supply-to-gulf-coast-pipeline-network.aspx

[12] Praxair, Pipeline https://www.praxairusa.com/industries/pipelines

[13] Global Carbon Capture and Storage Institute, 2019, "Global Status of CCS 2019" https://www.globalccsinstitute.com/resources/global-status-report/ The captured CO2 in this case is employed for enhanced oil recovery.

In still other cases, hydrogen may offer a climate-friendly route for preserving, modernizing, and expanding regionally and nationally important natural resource-dependent industries, such as iron ore mining and steel production. (See Box 3, Iron, Steel, and Hydrogen.)

BOX 3. IRON, STEEL, AND HYDROGEN

The iron and steel industry is carbon-intensive, accounting for about seven percent of global CO_2 emissions. While electric arc furnace steelmaking, which utilizes scrap and can use zero-carbon electricity, appears relatively straightforward to decarbonize, turning iron ore into steel with current commercial technologies is inherently carbon intensive. Such mills, in addition to requiring large amounts of typically fossil fueled energy for heat, traditionally use coal-derived coke to reduce (i.e., remove oxygen from) ore to make iron (sponge or pig iron) used in steel production, resulting in CO_2 emissions. Newer direct reduction ironmaking (DRI) uses natural gas instead of coke but still emits CO_2.

However, hydrogen can be used instead of coal or natural gas. Several European pilot projects are underway or being developed to reduce or eliminate CO_2 from steelmaking.[14] For example, ArcelorMittal is working to convert blast furnaces at two German steelworks to use natural gas, with plans to develop the facilities further to use hydrogen in conjunction with regional hub development.[15] A plant in Bremen would be part of a North German Clean Hydrogen Coastline network, utilizing renewably made (green) electrolytic hydrogen. The second, in Eisenhüttenstadt, would make “turquoise” hydrogen pyrolytically from natural gas pending development of an East Brandenburg hydrogen cluster.

Further north, in Sweden, energy utility, Vattenfall, has partnered with steelmaker SSAB and mining firm LKAB in the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) Initiative.[16] The initiative intends to deploy new technology to produce pilot scale fossil fuel-free sponge iron in 2021 to be followed by a demonstration plant in 2026 to produce 1.3 million metric tons per year of sponge iron. A full scale (2.7 million metric tons per year) plant is planned to operate by 2030. Zero-carbon (mainly wind) power will provide the energy for making green hydrogen.

These and other projects intend to demonstrate hydrogen pathways to decarbonize mining and heavy industries that are highly important to regional economies and employment. The primary challenge remains scale.

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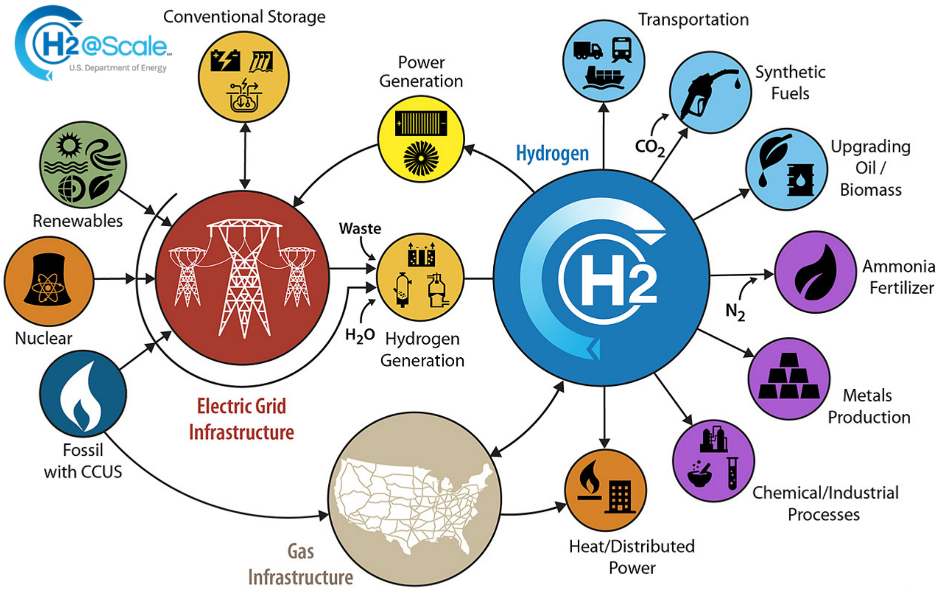
[14] Homann, Q., “Hydrogen as a Clean Alternative in the iron and Steel Industry,” Fuel Cell and Hydrogen Energy Association https://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry

[15] ArcelorMittal, “ArcelorMittal plans major investment in German sites, to accelerate CO2 emissions reduction strategy and leverage the hydrogen grid” (March 29, 2021) https://corporate.arcelormittal.com/media/news-articles/arcelormittal-plans-major-investment-in-german-sites-to-accelerate-co2-emissions-reduction-strategy-and-leverage-the-hydrogen-grid

[16] Vattenfall, Industry Decarbonization, “HYBRIT: A collaboration between SSAB, LKAB, and Vattenfall” https://group.vattenfall.com/press-and-media/pressreleases/2021/hybrit-ssab-lkab-and-vattenfall-to-begin-industrialization-of-future-fossil-free-steelmaking-by-establishing-the-worlds-first-production-plant-for-fossil-free-sponge-iron-in-gallivare

Figure 1 depicts the U.S. Department of Energy's H2@Scale concept, which envisions wide-scale and diverse hydrogen production and utilization in the United States, interlinking energy, power, transportation, and industrial applications and systems to provide energy resilience, economic competitiveness, employment, and environmental benefits.

FIGURE 1. H2@SCALE CONCEPT[17]



Source: U.S. Department of Energy

The left side of Figure 1 illustrates multiple routes to generating electric power, which can be used to make electrolytic hydrogen. The figure also shows hydrogen production paths directly from fossil fuels (with CCUS), biomass (a form of renewables), and waste.[18] The right side shows a diversity of hydrogen uses:

- as input for ammonia, metals (such as steel), and other chemical/industrial processes,
- as a direct fuel for transportation (via fuel cells or combustion),
- to upgrade petroleum and biobased fuels and produce synthetic fuels for transportation and other uses (e.g., alternatives to gasoline, diesel, and jet fuel) using captured CO_2,
- as a fuel for heating (space, water, steam, and industrial process heat) and combined heat and power ("heat/distributed power"), and
- to generate electric power for the grid when hydrogen is used as an energy storage medium.

Also notable in the figure (bottom portion) is the opportunity to link hydrogen with natural gas infrastructure. Hydrogen can be blended with natural gas and biologically-derived "renewable natural gas" to lower the carbon footprint of natural gas utilization. Portions of the natural gas infrastructure may also be usable as hydrogen infrastructure. However, the differing physical and chemical properties of hydrogen and natural gas impose blending limits for using existing pipes, equipment, and burners, which may or may not be able to be modified to operate with high-level blends or pure hydrogen.[19]

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[17] U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/h2scale, accessed November 1, 2021.

[18] Nuclear and solar energy can be used to thermally or photoelectrochemically to make hydrogen from water, but this is still at a research stage.

[19] Differing density, energy density, flammability, reactivity, and material compatibility (like hydrogen embrittlement of some types of steel and welds) may limit permissible hydrogen concentrations or require modifications to use hydrogen in some natural gas infrastructure and gas-burning equipment (like engines, boilers, and furnaces).

While the H2@Scale figure depicts hydrogen as an input for making climate-friendly synthetic fuels, it does not clearly note that ammonia (NH_3)—used in fertilizer and other products—can also serve as a hydrogen carrier for energy storage and transport, particularly for long distances.[20, 21] Ammonia can also be used as a fuel directly via combustion or, potentially, fuel cells for generating electricity, propelling ships, trains, and trucks, and for other uses. Ammonia is a commercially familiar product with well-established production, transport, and handling technologies and processes.[22] Like hydrogen, ammonia comes in a range of "colors" depending on carbon emissions footprints of production: ”brown” or ”gray” for conventional production, ”blue” if CCUS used, ”turquoise” if hydrogen is derived pyrolytically from natural gas, and ”green” if electrolytic green hydrogen used.[23]

Methanol, usually made from natural gas but renewably produce-able from green hydrogen and captured CO_2, can also be a hydrogen carrier. Like ammonia, it is commercially common and can be used directly as fuel. Unlike ammonia, CO_2 is released if used as fuel. Beyond methanol, there is research on other "liquid organic hydrogen carriers" (LOHCs) that could be stored and transported similarly to petroleum products.[24] There are tradeoffs in costs; energy requirements; and environmental, health, and safety risks between transporting, storing, and using hydrogen directly (including needs for high compression or very low temperature liquefaction) and employing ammonia, methanol or other LOHCs (including the costs and complexities of attaching then later extracting hydrogen from the carrier molecules).

The economic viability of the many hydrogen applications will depend on multiple interacting drivers and factors, including, among others:

- environmental policies and objectives such as for greenhouse gas emission reduction;
- research, development, and demonstration (RD&D) support;
- opportunities to create hydrogen hubs or clusters that achieve economies of scale and scope, including leveraging existing concentrations of industrial, electric power, and transport facilities, infrastructure, and expertise;
- development of industry standards especially regarding safety of production, storage, transmission, and distribution;
- siting and permitting processes; and
- public acceptance.

In the United States, natural gas-derived hydrogen costs around $1 per kilogram (kg) to produce and is estimated to be about $1.50 if CCUS is added.[25] U.S. DOE has a goal to reduce electrolytic hydrogen production cost to $2 per kg from current estimates of $5 to $6 per kg.[26] These costs are sensitive to underlying natural gas and electricity costs. At times of excess renewable generation, wholesale power prices can be near zero or even negative, making energy storage by battery or hydrogen less costly and more attractive.

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[20] NH3 Fuel Association https://nh3fuelassociation.org/.

[21] See, for example, Air Products, 2020, "Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets" (July 7, 2020) https://www.airproducts.com/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market regarding a project to produce green hydrogen to make green ammonia in Saudi Arabia for export by ship. There are also planned projects for internationally shipping liquefied hydrogen directly, analogous to liquified natural gas shipping; see Wang, F., 2020, "Australia-Japan Hydrogen Project Eyes Full Operations by Next Decade: Conference" (S&P Global, November 20, 2020)”https://www.spglobal.com/platts/en/market-insights/latest-news/coal/112020-australia-japan-hydrogen-project-eyes-full-operations-by-next-decade-conference

[22] However, there is research on alternatives to the conventional Haber-Bosch production process, including electrochemical synthesis.

[23] Tullo, A.H., 2021, "Is Ammonia the Fuel of the Future?," *Chemical & Engineering News* (Vol. 99, March 8, 2021) https://cen.acs.org/business/petrochemicals/ammonia-fuel-future/99/i8.

[24] Niermann, M., A. Beckendorff, M Kaltschmitt, and K. Bonhoff, 2019, "Liquid Organic Hydrogen Carrier (LOHC)—Assessment Based on Chemical and Economic Properties,' International Journal of Hydrogen Energy, Vol. 44, pp. 6631-6654, https://www.sciencedirect.com/science/article/abs/pii/S0360319919303581

[25] International Energy Agency, "The Future of Hydrogen" (2019) https://www.iea.org/reports/the-future-of-hydrogen, Fig. 9. About 50 cents of the cost is for natural gas.

[26] U.S. DOE, "Five Things You Might Not Know About H2@Scale," https://www.energy.gov/eere/articles/five-things-you-might-not-know-about-h2scale Cost estimates are based on 5 to 7 cents per kilowatt-hour electricity.

On the other hand, electrolyzers are most cost-effective at high utilization rates, suggesting higher costs if used only at times of excess generation, making this a fundamental conundrum for hydrogen production from variable generation.

As with renewable generation and batteries, costs have decreased with technological improvement, but more is needed to achieve cost-competitiveness. Electrolyzer improvements and cost reductions will depend on additional RD&D as well as scale of application.[27] The cost of hydrogen depends not only on production expenses but also on costs of processing, storage, and transport. Costs of end-use equipment, whether fuel cells or modifications to combustion or other equipment, should be considered too. RD&D is needed to improve the cost-effectiveness of high-pressure storage vessels, compression and liquefaction equipment, fuel cells, and modifications of industrial processes and equipment so they can use hydrogen. Advances are also needed to improve processes for making and using ammonia and other hydrogen carriers.[28] And CCUS advances can enhance the cost-effectiveness of blue hydrogen and blue ammonia. The costs are also sensitive to economies of scale and scope; multiple complementary producers and users can spread capital costs and improve utilization rates of facilities and equipment. Also, policies to meet greenhouse gas and other environmental objectives will affect the attractiveness of hydrogen.

State Energy Officials should be mindful that policies and regulations are important to the application of hydrogen. Pricing CO_2 emissions explicitly (e.g., by emission fees) or implicitly through regulated limits, clean electricity standards, and fuel carbon standards can incite demand for green or blue hydrogen, including for using hydrogen to store excess zero-carbon generation. Federal and state tax credits and incentives for reducing CO_2 emissions, for lower-carbon fuels, and for CCUS (such as the federal 45Q tax credit) can propel hydrogen viability.[29] Government provided or incentivized RD&D can advance technical and economic performance. Environmental, health, and safety standards for production, transport, storage, and use, and standards addressing material and equipment compatibility, are also important for an explosive gas with a global warming potential (GWP) of 4 to 6.[30] Federal, state, and local policies and procedures concerning facility siting and land use can support or impede environmentally favorable development of hydrogen and related infrastructure (including, as applicable, for CCUS), such as pipelines, electricity transmission, and storage facilities. Economic development incentives, including for investment and workforce development, can be important. State Energy Offices and other agencies may wish to consider policy, program, and regulatory options that can encourage hydrogen development and implementation that supports state economic and environmental objectives.

Among the resources included at the end of the paper, the International Energy Agency's The Future of Hydrogen (2019) discusses in more detail technical and economic aspects of hydrogen and hydrogen-based materials production; storage; transport and distribution; uses and applications; and policy-related facets. Columbia University's Center on Global Energy Policy in their 2021 Report on Green Hydrogen in a Circular Carbon Economy: Opportunities and Limits also explores the technology readiness for hydrogen production. NASEO welcomes suggestions for additional resources as well as information on pertinent initiatives, cases, planning efforts, policies, and regulations.

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[27] Alkaline, proton exchange membrane (PEM), and solid oxide (SOEC) electrolyzer technologies are available with the solid oxide technology least mature. SOECs use steam so may be well-suited for some industrial and power sector (nuclear, geothermal) locations; also, they can be operated in reverse as fuel cells to generate electricity from hydrogen.

[28] For example, the U.S. DOE-supported Ammonia-Based Energy Storage Technology (NH_3-BEST) project at the University of North Dakota is developing an electrolytic ammonia synthesis technology as well as fuel cells capable of using ammonia directly to generate electricity. https://netl.doe.gov/sites/default/files/netl-file/21AES_Aulich.pdf

[29] See NASEO, 2021, "Carbon Capture, Utilization, and Storage: Overview and Considerations for State Planning" and related web pages for coverage of CCUS, https://www.naseo.org/issues/energy-environment-climate/ccus.

[30] GWP is relative to carbon dioxide over a 100-year time horizon. Derwent, R.G., 2018, "Hydrogen for Heating: Atmospheric Impacts—A Literature Review," Department for Business, Energy and Industrial Strategy (U.K.), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf ; Derwent R., P. Simmonds, S. O'Doherty, A. Manning, W. Collins and D. Stevenson, 2006, "Global environmental impacts of the hydrogen economy," Int. J. of Nuclear Hydrogen Production and Applications, Vol. 1, pp. 57-67, http://agage.mit.edu/publications/global-environmental-impacts-hydrogen-economy

State Energy Planning and Policy Considerations

State Energy Offices can consider whether and how hydrogen can fit into their state's energy, environmental, and economic development plans and strategies. Consistent with questions below, planners should consider their state's energy and climate-related objectives; potential electricity and natural gas system synergies; existing and emerging industrial opportunities; potential transportation applications; CCUS linkages; and regional options for achieving economies of scale and competitive advantage. State Energy Offices could benefit by taking stock of current and prospective federal and state policies and regulations that will affect hydrogen viability and opportunity. These questions can also be explored in partnership with relevant hydrogen industry players and major end-users and offtakers.

The following questions and issues are for state energy planning consideration:

- **What are current and prospective electricity systems needs for energy storage?** States may wish to consider how opportunities and needs for energy storage may develop as generation and consumption patterns change. Increasing variable renewable generation, electrification of transportation and other end uses (e.g., heating, hot water), and emissions goals may necessitate energy storage. State Energy Offices could evaluate potential storage needs, including scale and duration of storage (hours to seasonal), and how hydrogen may fit relative to batteries, pumped hydro, compressed air, and other options. Additional considerations are potential safety regulations of energy storage.
- **What opportunities are there for leveraging and "greening" existing oil, natural gas, and chemical industry facilities, infrastructure, and expertise?** Hydrogen development can provide a means to leverage existing fossil fuel-based facilities, workforce, and expertise in a more climate-friendly manner while preserving or expanding economic value and employment. State Energy Offices could consider potentials for blending hydrogen with natural gas in existing or modified infrastructure, augmenting or repurposing oil and gas facilities and pipelines for hydrogen and CCUS, and applying the skills of the natural gas, oil, and petrochemical workforce to hydrogen-based production, including production of ammonia and other hydrogen carrier chemicals.
- **What opportunities are there for hard-to-electrify/hard-to-decarbonize industrial and transportation applications?** States could consider opportunities for hydrogen in hard-to-electrify and hard-to-decarbonize sectors and applications. Hydrogen, sometimes linked with CCUS, can offer net-zero carbon and low pollution pathways for iron and steel, cement, ammonia, and other production, in some cases with hydrogen serving as both material and energy inputs. However, technological and financial hurdles remain. Heavy duty and long-haul trucking, rail, marine, and, potentially, aviation transportation also may be propelled by hydrogen or hydrogen-derived ammonia or synthetic fuels, perhaps in competition with electric propulsion. State Energy Offices could consider potential roles for hydrogen to modernize and strengthen relevant manufacturing industries and transportation hubs, such as ports, rail depots, and airports.
- **Are there potential economic development synergies?** Spreading the cost of pipelines, compressors, storage, site development, and other components of hydrogen infrastructure and, as warranted, complementary CCUS over large volumes of the gases serving multiple entities can reduce cost per ton significantly. Regional concentrations of producers and users, perhaps with linkages to suitable geology for underground hydrogen storage and, as applicable, CCUS can provide economies of scale. They can become hubs or clusters that also achieve agglomeration economies where the concentration of experience, expertise, and physical capital can encourage additional productivity, innovation, and investment,

including in new technologies and applications and in supportive supply chain businesses. As noted earlier, hydrogen may offer means for existing physical and human capital from oil, gas, and petrochemical industries to be leveraged, extended, and adapted to a net-zero carbon emissions economy. In considering economic development opportunities, State Energy Office planners could also take stock of pertinent research and expertise in their colleges and universities, national laboratories, private firms, and non-governmental organizations that can be tapped to evaluate and develop opportunities, advance technologies, and build skilled workforces.

- **What are current and prospective policy and regulatory environments?** Federal, state, and local policies and rules greatly affect the economic viability of hydrogen, providing both impetus and impediment to development of technologies, investment in facilities and infrastructure, and commercial implementation. Greenhouse gas and other environmental policies have critical importance and can be the main driver of hydrogen's viability. RD&D and economic development policies are also important for advancing technologies and making them commercial. Various other policies, rules, and processes, including, among others, siting and land-use procedures, government procurement, and underground rights and liabilities, are also pertinent. Some of these aspects are summarized below.
- **What are the policy and regulatory barriers at the state level that need to be removed for hydrogen to enter the market and become a viable solution?** While costs are certainly still a barrier for hydrogen solutions, policies and regulations can often become hurdles as well, especially as hydrogen spans many different sectors such as transportation, electricity, and industrial sectors.

Often states will begin to answer these questions by developing a roadmap or strategy for hydrogen (See Box 4: State Planning Options for Considering Hydrogen).

BOX 4: STATE PLANNING OPTIONS FOR CONSIDERING HYDROGEN

In 2021, the Oregon legislature passed a bill requiring the Oregon Department of Energy "to conduct a study of the potential benefits of and barriers to production and use of renewable hydrogen in Oregon."[31] The report, slated to be published in September 2022, will examine the amount of hydrogen currently used in Oregon; potential applications of renewable hydrogen in Oregon by 2030; an assessment how renewable energy and renewable hydrogen could be coupled for grid and resilience benefits; the potential cost curve of renewable hydrogen; and technological barriers. The bill also defined renewable hydrogen in Oregon as hydrogen that is produced from sources that do not emit greenhouse gases. New York announced in July 2021 that it will study the role of green hydrogen for the states' decarbonization goals. The New York State Energy Research and Development Authority (NYSERDA) is partnering with the National Renewable Energy Laboratory (NREL) on aligning New York's hydrogen strategy and mandates to eliminate emissions from the electricity sector by 2040. The state will also support long-duration energy storage technologies through a $12.5 million grant funding. Additionally, the New York Power Authority (NYPA) will collaborate with other organizations on green hydrogen demonstration project at NYPA's Long Island natural gas plant.[32]

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[31] Oregon Department of Energy, 2021 Legislative Report, https://www.oregon.gov/energy/Data-and-Reports/Documents/2021-Legislative-Session-Report.pdf

[32] NYSERDA, Governor Cuomo Announces New York Will Explore Potential Role of Green Hydrogen as Part of Comprehensive Decarbonization Strategy, https://www.nyserda.ny.gov/About/Newsroom/2021-Announcements/2021-07-08-Governor-Cuomo-Announces-New-York-Will-Explore-Potential-Role-of-Green-Hydrogen

The following issues are for state energy policy consideration:

- **RD&D and Commercialization Assistance.** Federal and state governments can support relevant RD&D directly through funding and encourage private funding through tax incentives. Similarly, states can directly support and can encourage private, university, and philanthropic backing of "clean tech" incubators, accelerators, and related technical and business assistance. State economic development programs that target clean tech and "greening" of economic sectors can help advance hydrogen as well as other relevant technology development, commercialization, and deployment.[33]
- **Emission Limits and Price on Carbon.** A price on carbon (CO_2 or greenhouse gases broadly) through a fee or, indirectly, through regulated limits (including use of tradable allowances) can encourage blue and green hydrogen use. Storing excess and off-peak zero-carbon electricity generation as hydrogen or otherwise (e.g., batteries, pumped hydro) reduces reliance on fossil fueled generation. Also, hydrogen and derivative carriers (such as ammonia) can replace fossil fuels directly in industrial, heating, and transportation uses. States could consider fees, taxes, or other charges on fossil fuels or emissions. They can impose regulated emission limits, such as for power generation in the Regional Greenhouse Gas Initiative (RGGI) states, which auction and allow trading of emission allowances by regulated power producers.[34] Similarly, California's Low Carbon Fuel Standard regulates the carbon intensity of transportation fuels used in the state, allowing fuel providers to trade credits for compliance.[35] States could design policies so compliance focuses on in-state actions and resources or they could consider regional approaches that may lower compliance costs and strengthen economic development synergies, including for related CCUS options.
- **Clean Energy/Renewable/Alternative Energy Standards and Low Carbon Credits.** Thirty states, the District of Columbia, and three territories have Renewable, Clean Energy, and/or Alternative Energy Portfolio Standards that require electric utilities[36] to deliver a portion of their electricity from eligible sources.[37] A growing number of states and utilities are aiming for 100 percent zero-carbon generation goals. Like a price on carbon, these requirements and targets can incentivize hydrogen energy storage to enhance renewable and nuclear generation supply and reduce fossil fueled generation. As noted previously, low-carbon fuel standards can incentivize hydrogen and other low- and non-carbon fuel options.
- **Tax and Fiscal Incentives.** Federal and state tax incentives can support hydrogen-related RD&D and deployment as well as complementary investments in hydrogen applications and CCUS. States can consider offering tax credits, deductions, exemptions, and other incentives for relevant investments. The federal Internal Revenue Code Section 45Q income tax credit for CCUS can help stimulate blue hydrogen production and use.[38] Investment and production tax credits for hydrogen applications or, more broadly, for renewable and (net) zero-carbon generation (perhaps including fossil fueled with CCUS) can also be supportive. The California

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[33] The NASEO Energy Technology Innovation https://naseo.org/issues/technology-innovation has relevant discussion and resource links as well as content on State Energy Office roles and programs https://naseo.org/issues/technology-innovation/seo-roles.

[34] Regional Greenhouse Gas Initiative, "RGGI, Inc." https://www.rggi.org/index.php/rggi-inc/contact RGGI states include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia. Pennsylvania has expressed interest in joining.

[35] California Air Resources Board, 2019, "Carbon Capture and Sequestration Project Eligibility FAQ." https://ww2.arb.ca.gov/resources/fact-sheets/carbon-capture-and-sequestration-project-eligibility-faq

[36] Depending on state, requirements may apply only to investor-owned utilities or may include consumer-owned public power and cooperative utilities as well. Requirements may also vary by utility size.

[37] National Conference of State Legislatures, "State Renewable Portfolio Standards and Goals" https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

[38] 45Q provides an income tax credit of $20 per metric ton CO_2 geologically stored and $10 per metric ton used for enhanced oil or gas recovery. The credit will rise a 2026 rate $50 per metric ton geologically sequestered and $35 per metric ton used in oil or gas recovery. Qualified facilities must begin construction by January 1, 2024 and meet size and other criteria. U.S. Department of Energy (2019), "Internal Revenue Code Tax Fact Sheet" https://www.energy.gov/sites/prod/files/2019/10/f67/Internal%20Revenue%20Code%20Tax%20Fact%20Sheet.pdf

Energy Commission (CEC) through its Clean Transportation Program is providing grant funding for renewable hydrogen. The most recent $7 million grant announced in 2021 aims to fund projects to develop a hydrogen facility in California that will produce renewable hydrogen from in-state renewable energy resources. The hydrogen will then be used for transportation fuel for light-duty and medium-/heavy-duty fuel cell electric vehicles. Among others, the program supports the Clean Transportation Program's goal to "reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies [as well as to] produce sustainable alternative and renewable low-carbon fuels in California."[39]

- **Government procurement.** Government procurement can be a tool to stimulate markets for new technologies and processes. Federal, state, and local government "green" procurement and lead-by-example policies have stimulated green and energy-efficient building construction, energy-efficient equipment, renewable energy and alternative fuels, recycled materials, and products with reduced toxic material content. States could consider requirements or preferences for buying renewable or zero-carbon electricity, which could indirectly advance hydrogen and other electricity storage too. Low-carbon fuel procurement preferences could help incite hydrogen as well as biogases, including blending with natural gas. States could also consider the life-cycle carbon and wider environmental impacts of the products and materials they buy, giving preference to lower carbon footprint products, such as steel, cement, fertilizer, and other products produced using blue or green hydrogen.[40] For example, Colorado's "Buy Clean Colorado" policy requires the Office of the State Architect and Department of Transportation to establish policies regarding the embedded global warming potential for eligible materials to be procured to construct certain projects, like public buildings, bridges, and roads.[41]
- **Technical and environmental, health, and safety standards.** States could work with the federal government, industry, labor, first responders, local officials, the research community, and others to support the development of and training on codes and standards for handling and using hydrogen. Limits and tolerances will need to be established for blending hydrogen with natural gas to assure safety and compatibility with existing, modified, and new infrastructure and equipment. Environmental, health, and safety (EHS) codes and standards are needed for facilities and equipment that produce, store, convey, and use hydrogen, and pertinent training is needed for workers, code officials, and first responders.

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[39] California Energy Commission,GFO-20-609 Renewable Hydrogen Transportation Fuel Production, https://www.energy.ca.gov/solicitations/2021-04/gfo-20-609-renewable-hydrogen-transportation-fuel-production

[40] And turquoise too—solid carbon recovered from pyrolytic hydrogen production can be used in tires and other rubber products, pigments, and other applications.

[41] Colorado General Assembly, 2021, HB21-1303: Global Warming Potential for Public Project Materials, https://leg.colorado.gov/bills/HB21-1303

- **Financing.** Private activity bonds (PAB) can be made available by states, with federal permission, to secure low-cost, long-term fixed rate debt for qualifying projects. For example, the Wyoming Infrastructure Authority was created by the Wyoming legislature in 2004 to advance infrastructure development and was authorized to issue up to $1 billion to finance energy infrastructure.[42] States could make PAB bonding available for hydrogen and CCUS projects. Several states, including California, Connecticut, Hawaii, New York, and Rhode Island, have green banks that offer loans, loan guarantees, and other credit enhancements and services to advance clean energy development and deployment.[43] State-affiliated green banks and infrastructure banks can be authorized and encouraged to support hydrogen projects. States could also choose to directly fund or finance pertinent projects. Hawaii established a Hydrogen Investment Capital Special Fund, which supported the Hawaii Hydrogen Power Park.[44]
- **Infrastructure planning and support.** States, individually and regionally, and in cooperation with the federal government, could consider opportunities for coordinated infrastructure planning. Electricity transmission, hydrogen piping, CO_2 piping (as applicable for CCUS), and associated facility investments would benefit from coordination that provides economies of scale and scope and, where appropriate, take advantage of existing industries, infrastructure, and expertise. An analogy is made with how Texas unleashed a large, vibrant wind power industry by creating competitive renewable energy zones (CREZ) that facilitated the construction of high voltage transmission lines to bring abundant wind power from west Texas to meet the needs of populous central and southeastern Texas.[45] Similarly, states and regions, in collaboration with federal authorities, can help multiple parties to coordinate project and infrastructure development.
- **Siting and permitting.** Hydrogen pipelines, complementary electric transmission and, if applicable, CO_2 pipelines may be subject to federal, state, and local siting procedures, land-use regulation, and environmental permitting requirements. Such requirements may also apply to surface and underground hydrogen storage, compressor stations, terminals and depots, and other facilities, including associated CCUS facilities and sequestration sites. States can pay attention to such processes and requirements and, where warranted, try to streamline reviews and approvals.
- **Subsurface Ownership and Long-term Liability.** Subsurface ownership rights and potential liabilities can be issues that affect site development for underground hydrogen storage as well as for any complementary CCUS implementation. Montana, North Dakota, and Wyoming passed laws pertinent to CCUS to clarify ownership of injected gases and of the pore space into which they are injected. The three states also set requirements for landowner consent needed for projects to proceed.[46] Liabilities for leakage and accidents and monitoring and management of underground storage may also require attention.

These high-level questions and considerations will likely generate more detailed questions for deliberation by State Energy Offices and other pertinent planners and policymakers.

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[42] State CO2 -EOR Deployment Work Group, 2016, cited in Zitelman, K. et. al., “Carbon Capture, Utilization, and Storage: Technology and Policy Status and Opportunities,” National Association of Regulatory Utility Commissioners, November 2018 https://pubs.naruc.org/pub/03689F64-B1EB-A550-497A-E0FC4794DB4C

[43] National Renewable Energy Laboratory, “Green Banks” https://www.nrel.gov/state-local-tribal/basics-green-banks.html

[44] U.S. Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/laws/6079, accessed November 1, 2021.

[45] Lasher, W., 2014, “The Competitive Renewable Energy Zone Process” ERCOT https://www.energy.gov/sites/prod/files/2014/08/f18/c_lasher_qer_santafe_presentation.pdf in Ziterman, et al. op cit.

[46] Zitelman, K. et. al., 2018, “Carbon Capture, Utilization, and Storage: Technology and Policy Status and Opportunities,” National Association of Regulatory Utility Commissioners, https://pubs.naruc.org/pub/03689F64-B1EB-A550-497A-E0FC4794DB4C.

Conclusions

Hydrogen offers pathways to a clean energy system and climate-friendly industrial processes that can grow economic and employment opportunities in new industries and also leverage and evolve existing industries, facilities, and expertise.

Current hydrogen production and uses in petroleum refining and ammonia production may be dwarfed in years to come by opportunities to:

- store excess and off-peak zero-carbon electricity at large scale and for long terms (days to seasonal) to enhance electricity system resilience, economic performance, and emission reduction,
- decarbonize hard-to-electrify chemical, metal, and material production processes,
- leverage and extend fossil fuel-based resources, infrastructure, and expertise for cleaner energy and industrial applications, and
- power transportation, including heavy-duty truck, rail, marine, and, perhaps, aviation modes.

State Energy Officials may wish to consider the potential and opportunities for hydrogen in their states' energy, environmental, and economic development policies and planning.

Resources

- International Energy Agency
    - The Future of Hydrogen (2019)
- (U.S.) Hydrogen and Fuel Cells Interagency Working Group:
- U.S. Department of Energy
    - Hydrogen Program
        - Hydrogen Program Plan
    - Hydrogen and Fuel Cell Technologies Office
        - Hydrogen Fuel Basics
    - Alternative Fuels Data Center
        - Hydrogen Production and Distribution
- U.S. Department of Energy National Laboratories
    - Argonne National Laboratory
        - Assessment of Potential Future Demands for Hydrogen in the United States (2020)
    - National Renewable Energy Laboratory
        - Hydrogen and Fuel Cells
        - Resource Assessment for Hydrogen Production (2020)
        - The Technical and Economic Potential of the H2@Scale Concept within the United States (2020)
- Bloomberg New Energy Finance, "Hydrogen Economy Outlook: Key Messages"
- British Columbia Hydrogen Study
- Circular Carbon Economy
    - Zapantis, A., "Blue Hydrogen" Global CCS Institute (2021)
- Clean Hydrogen Future Coalition
- Energy Transitions Commission
    - "Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy"
- European Commission. 2020. "A Hydrogen Strategy for a Climate Neutral Europe"
- Fraunhoffer Institute for Energy Economics and Energy System Technology
    - Gerhardt, N., J. Bard, R. Schmitz, M. Beil, M. Pfennig, T. Kneiske, "Hydrogen in the Energy System of the Future: Focus on Heat in Buildings" (2020)
- Fuel Cell and Hydrogen Energy Association
    - Roadmap to a U.S. Hydrogen Economy
- Green Hydrogen Coalition
- H21 Pioneering a UK Hydrogen Network
- Hydrogen Forward
- NH3 Fuel Association
- Western Green Hydrogen Initiative
- Energy Futures Initiative, The Future of Clean Hydrogen in the United States (2021)

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