WHITE PAPER

EXPLORING THE FUTURE ROLE OF HYDROGEN IN A DECARBONIZED POWER INDUSTRY

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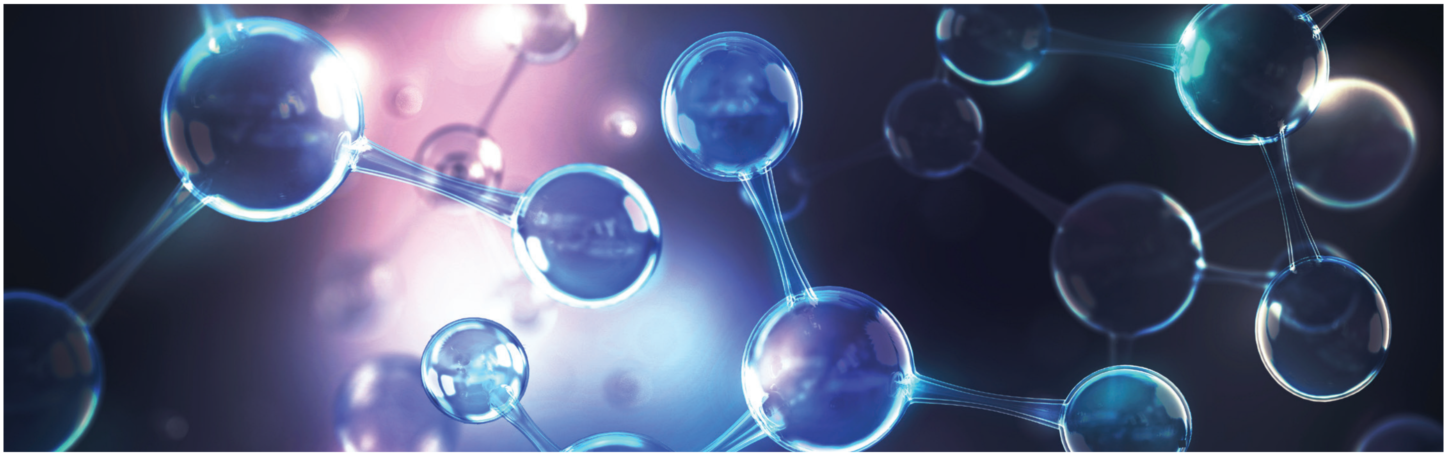
As hydrogen reemerges as a key technology for electric power, utilities can consider its ability to reduce emissions and enable carbon-free dispatchable generation.



Electric utilities and generation owners are under pressure to reduce the fossil carbon intensity of their fleets, with some regional governments mandating resource mixes that are either fossil-free or produce net zero carbon emissions by a given year, typically between 2030 and 2050. These regulatory pressures are driving an increase in renewable-heavy portfolios: As of January 2021, at least seven states and over 200 cities and municipalities had legislative mandates for attaining 100% carbon-free power within this time frame. Large businesses are exercising their market power too, with more than 250 corporate members of the RE100 global initiative setting 100% renewable or carbon-free power goals.

Offsetting fossil fuels with renewable alternatives as a primary energy source, along with a growing concentration of variable resources on the grid, poses both challenges and opportunities that are not readily met with existing grid-scale technologies. A new solution is needed, and hydrogen is becoming acknowledged as a potentially key technology in the evolution of the electric power industry.

A Versatile Fuel

Hydrogen (chemical symbol H) is the lightest of the elements, which are the simplest chemical building blocks of all matter. It is the most abundant element in the universe, and the third-most-plentiful element on Earth. However, pure hydrogen is rarely found in nature. It cannot be mined or drilled from natural deposits. Most of the hydrogen on Earth is bound together with oxygen as water (H_2O) or found in biological matter and as a component of fossil fuels.

In typical industrial applications, hydrogen is encountered as a light, flammable gas. Hydrogen gas is odorless, nonreactive, nontoxic and nonpolluting. However, it does form flammable mixtures with air over 4% to 75% concentration spans, which is a wide range compared to natural gas (5% to 15%), but less than some other industrial gases such as acetylene (2.5% to 100%). Hydrogen burns in air to form heat and steam, with no carbon dioxide emitted. Like most fuels, certain hydrogen-air mixtures can be made to explode, but hydrogen itself is not explosive. Hydrogen is widely used in industries, with about

50% of total world production used with ammonia, mostly used for fertilizers, followed by oil refining at over 25%.

Typical materials used for industrial process equipment are compatible with hydrogen, including carbon steel, most stainless steels and elastomers, although some metals can be embrittled by hydrogen at higher pressures and/or temperatures as the light gas diffuses into the structure of the metal. Nonetheless, hydrogen is an established commodity, and its handling is well understood. Hydrogen can be liquefied at very low temperatures, 20.28 K (-252.87° C or -423.17° F), greatly increasing its density for storage or transportation. While hydrogen liquefaction is also a mature industrial technology, it is energy intensive, requiring up to 30% of the energy content of the hydrogen to be liquefied.

Production

Most of the world's supply of hydrogen is produced from fossil fuels in processes such as steam methane reforming (SMR) of natural gas or gasification of coal. SMR is common in North America and Europe, while China uses the gasification pathway extensively. Both production methods emit CO_2 to the atmosphere. Fossil-produced hydrogen could be made carbon neutral by capturing the produced CO_2. Carbon capture — a set of processes that capture CO_2 emissions before they are released to the atmosphere for industrial uses or underground sequestration — is not widely used for decarbonization of energy production at this time. Economically and technically viable methods of carbon capture could allow fossil fuels to be a part of the decarbonization technology mix in future years. Less common sources of hydrogen are gasification of biomass, with or without carbon capture, and hydrogen production with heat and/or electricity supplied from nuclear sources.

Hydrogen production from renewable electricity is largely by electrolysis of water. Electrolysis systems use electric power to form hydrogen and oxygen gases, along with byproducts of water and possibly heat. When power is supplied from renewable sources — a process commonly categorized as green or yellow — the hydrogen produced is considered a renewable resource. The core technologies for electrolysis have existed for decades and in general are ready for commercial deployment, but a historical lack of interest in renewable hydrogen compared to that produced by fossil sources has resulted in few large-scale installations. Growth in renewable hydrogen production does not require a breakthrough technological development, but rather scaling up of worldwide production capacity that is already underway by major manufacturers.

Similar to fossil-produced hydrogen with carbon capture, both the biomass and nuclear pathways may not be considered universally renewable by regulatory bodies as regulatory frameworks develop. For example, California's Renewable

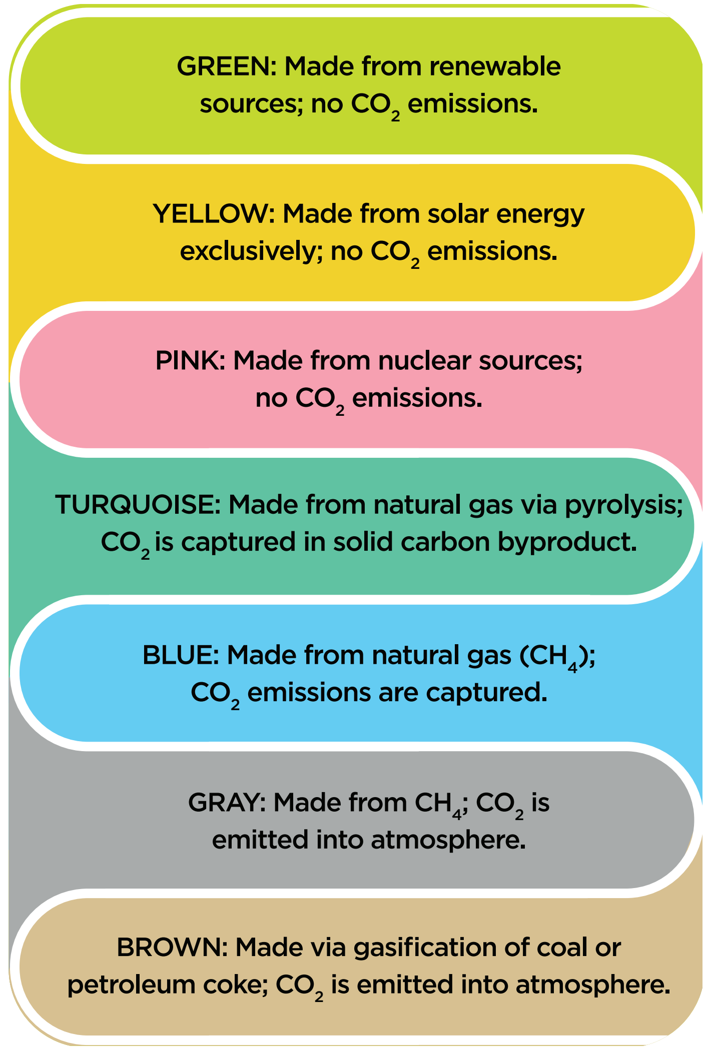


***Figure 1:** An informal color rainbow widely used to categorize energy sources, production processes and relative emissions of hydrogen is evolving as variables continue to shift.*

Portfolio Standard (as set in 2020) considers hydrogen renewable only if produced from certain biomass sources, and not from nuclear energy. However, these sources may be allowed by other regulators, opening up further opportunities for incentivized deployment of hydrogen technology. Renewable standards can guide the development of projects, because incentives applied to qualifying renewable generation can influence the economic viability of a project.

Transportation

Hydrogen can be transported through underground steel pipelines, or by road and rail in compressed gas cylinders or as refrigerated liquid hydrogen in vacuum-insulated low-pressure tanks. Hydrogen pipelines tend to be concentrated around petrochemical industrial zones and generally do not have extensive geographical coverage compared to petroleum and natural gas pipelines. However, it is possible to convert existing petroleum and gas pipelines to carry hydrogen with appropriate upgrades to sealing systems and compressor stations.

Storage

Some hydrogen storage capacity exists today at hydrogen production facilities, although the aggregate is much less than would be required for use of hydrogen as a bulk energy storage medium. A few large-scale storage installations exist in underground salt domes, such as those on the U.S. Gulf Coast supporting the petroleum industry and those being developed in western Utah for energy storage. Suitable geology for salt dome storage is relatively rare worldwide, although attempts are being made to develop hydrogen storage fields using other rock formations or even abandoned oil and gas reservoirs.

For regions where geological storage is not feasible, hydrogen can also be stored and transported in the form of other simple chemical products. Ammonia, made of hydrogen and nitrogen — itself easily separated from air — is the leading candidate. Ammonia liquefies under relatively mild conditions, similar to propane, to an energy density very close to that of liquid hydrogen, without the technical challenges and energy intensity of forming the ultra-cryogenic liquid. Liquid ammonia shipments by rail, road, sea and pipeline are established procedures. Ammonia can be used as a fuel in specially designed combustion equipment, including combustion turbines and fuel cells, or converted back to hydrogen. Forming ammonia from green hydrogen demands more energy than hydrogen alone and subsequently carries an efficiency penalty for energy storage, even though ammonia may prove superior for long-distance transmission and long-term storage because of the reduced energy requirements to compress and liquefy ammonia.

The Electric Power Perspective

The power industry is starting to consider hydrogen as one of the key links between variable renewable power generation sources and a stable, decarbonized grid. Hydrogen can support the management of variable generation with electrolyzers utilizing excess power that would otherwise be curtailed and then using the hydrogen produced to fuel combustion turbines and other equipment generating power to cover shortfalls. Large-scale hydrogen storage could enable carbon-free dispatchable generation, or seasonal shifting by banking large volumes of hydrogen in deep caverns or large tanks that could be called upon as needed.

While hydrogen technologies are a conceptually attractive solution for some of the problems posed by evolving power markets, there are few existing large-scale deployments. Since hydrogen is not a primary energy source, as it cannot be mined or drilled from the Earth, primary energy like fossil fuels or renewable power must be spent to produce it, making hydrogen more expensive than fossil fuels. This paradigm is likely to continue so long as the major outstanding externality of fossil fuel combustion — CO_2 emissions to the atmosphere — remains cost free. In the current energy economy, there are few jurisdictions that impose a financial penalty of any kind on CO_2; subsequently, there are few current applications for green hydrogen. Economic drivers such as a penalty for emitting CO_2 or a regulatory guideline restricting the emission of CO_2 will be required to make hydrogen a more significant participant in the energy economy.

An Incentive-Driven Market

The value of green hydrogen in the electric power industry, and in the energy industry as a whole, is almost entirely due to its ability to concentrate renewable power in a carbon-constrained world. The point when hydrogen becomes an economical part of the energy landscape depends on the regulatory framework in a given jurisdiction. The energy industry is an incentive-driven market and hydrogen won't achieve cost parity with fossil fuels absent a regulatory environment that imposes additional costs on fossil energy or limits nonrenewable CO_2 emissions.

Even without global consensus on carbon pricing, hydrogen projects are developing in strategic markets:

- In the U.S., regions with large renewable penetration can experience excess production that results in depressed power prices and loss of revenue from curtailed assets. The utility NextEra Energy is taking advantage of such a situation to develop a 20-megawatt (MW) electrolyzer project to use excess renewable power to produce hydrogen for blending into the natural gas fuel for a combined-cycle power plant.
- In Europe, where carbon pricing is being phased in, Fertiberia's fertilizer plant is offsetting up to 10% of its natural gas consumption with a 100-MW solar field and electrolyzer plant.
- Saudi Arabia is teaming with U.S. chemical manufacturer Air Products on a global-scale green hydrogen and ammonia project using abundant renewable power in the Saudi desert, anticipating a rise in corporate demand for green chemical feedstocks, especially in Europe
- The Los Angeles Department of Water and Power (LADWP), along with Magnum Development, is planning to build a combined-cycle replacement for the coal-fired Intermountain Power Plant in Utah. The replacement will be able to fire up to 30% hydrogen on startup, with plans to eventually increase to 100% hydrogen firing. Nearby salt domes will be developed for bulk energy storage.

- A similar combined-cycle project is underway in Ohio, which will burn up to 20% fossil-sourced hydrogen upon startup. It is being built in anticipation of eventual conversion to green hydrogen and also has nearby salt formations.

In the short term, the first three publicly announced projects are examples of current market opportunities for the electric industry to begin piloting hydrogen projects and developing operational experience. Areas with significant excess renewable capacity can direct that production toward electrolysis rather than simply curtailing it. Natural gas blending is being widely discussed by utilities and power producers as an ideal application for intermittently produced hydrogen. Hydrogen blends easily into natural gas and while the maximum hydrogen concentration must be evaluated for each system, many believe that hydrogen blends between 5% and 15% may be possible without extensive upgrades. The blended gas can offset some of the natural gas cost of nearby generating facilities or be blended into the larger distribution network to reduce the overall carbon intensity of natural gas operations.

Natural gas blending is ideal for intermittent hydrogen production, too, since expensive storage would not be required to smooth out unsteady production. Converting existing plants, especially combustion turbine plants, to burn blended or pure hydrogen could help extend the life of these expensive assets well into the future. Most models of combustion turbines can be converted to burn blended or pure hydrogen with modifications to fuel handling and combustor systems, with the extent and magnitude of modifications dependent upon the turbine model, age and other factors.

A number of leading reciprocating engine and combustion turbine manufacturers are developing units that can burn 100% hydrogen fuel. Demonstration 100% hydrogen projects could be operational by 2023, and commercial-scale plants may be coming as soon as 2025.

Another likely growth area is hydrogen production for vehicle fueling. Large trucks and heavy equipment are not as easily converted to battery electric power as passenger cars. Hydrogen engines or fuel cells are a more natural fit for commercial and heavy construction applications.

Dedicated hydrogen production for industrial users is expected to grow as carbon regulations are implemented. Ammonia is a natural industry to pilot renewable hydrogen production since the ammonia production process itself would not change, only the source of the hydrogen feedstock. Other industrial applications are envisioned. Hydrogen could replace fossil-derived blast gas as the reductant in blast furnaces, reducing the carbon intensity of steelmaking. Burns & McDonnell has even been approached by oil refiners looking to integrate green hydrogen as a means to get ahead of possible carbon regulations. These applications offer a growth market for load to the electric industry, since much of the primary energy to make this industrial green hydrogen is likely to come from electric sources.

The LADWP project gives a glimpse into a possible future for hydrogen as an energy storage medium. The renewable generation that will be required to meet zero-carbon legislative mandates needs a dispatchable backstop with days or weeks of capacity to maintain production during poor renewable output or periods of high grid demand. Green hydrogen, or synthetic fuels produced from it, can meet that need in a way most other energy storage options cannot, simply by virtue of scale. The salt domes being developed have the potential to store weeks' worth of fuel. It should be noted that jurisdictions that allow a small proportion of fossil capacity (even as little as 10%) or nuclear generation will need much less bulk energy storage than areas with only renewable sources.

Putting It All Together

Utilities are beginning to recognize hydrogen technologies as future contributors to the electric power industry. Hydrogen will likely only displace fossil fuels as legislatures and regulators impose costs or limits to CO_2 emissions. If the current worldwide trend toward carbon regulation continues, hydrogen is expected to take on several roles as fossil fuel assets are retired.

In the near term, hydrogen production as a means to absorb excess renewable power offers a convenient opportunity to pilot hydrogen projects. The produced hydrogen will be most economically directed toward natural gas blending and vehicle fueling. When carbon limits begin to affect commodity chemicals, such as ammonia, larger electrolyzer plants will be needed, making hydrogen either a new source of user load or even a new revenue stream for utilities that offer hydrogen in their suite of products with electric power and natural gas.

In the long term, hydrogen and synthetic fuels used for energy storage are likely to become major components of the power industry in regions that phase out fossil fuels completely. Hydrogen or ammonia pipelines are likely to serve similar functions as today's high-voltage electric transmission lines, moving energy from sources of production to areas of high consumption. Hydrogen in energy storage will compete with nuclear power, long-distance power transmission lines, and other forms of high-capacity storage like compressed air and pumped hydro.

Overall, while the form of the market cannot yet be predicted, hydrogen seems increasingly likely to play a role in a decarbonized electric industry. Even now, with few CO_2 restrictions fully imposed, investment opportunities are emerging. Electric utilities have the opportunity to be major participants in the evolution of hydrogen as an energy commodity and in the growth of the hydrogen supply business.

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