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As nuclear-powered water electrolysis becomes cheaper, it could compete with the current, carbon-intensive hydrogen production process.

Struggling to defend its market share from lower-cost electricity produced from natural gas and renewables, the US nuclear industry is tentatively exploring a new revenue source: hydrogen production. The US Department of Energy is encouraging that potential repurposing by providing more than $84 million for improving electrolyzers that split water and for installation demonstrations at two commercial nuclear power plants.

The growth of low-cost wind and solar power and an abundance of cheap shale gas have made higher-cost nuclear power often unprofitable (see PHYSICS TODAY, December 2018, page 26). "It doesn't make sense to downwardly dispatch a perfectly running nuclear plant," said Michael Green, general manager of nuclear policy at Pinnacle West Capital, the holding company for the utility Arizona Public Service. A hybrid plant producing hydrogen and electricity would provide an outlet for the nuclear power that is now sold at a loss.

In one DOE-backed project valued at $7.2 million, Exelon, the country's largest nuclear plant operator, will install a 1 MW electrolyzer at one of its 21 reactors. DOE will split the cost with the utility giant. Exelon plans to complete the demonstration in April 2023 and will use the hydrogen it produces on-site. Hydrogen gas is commonly used to cool and provide a low-drag environment in electricity-generating turbines. Three national laboratories and Norway's Nel Hydrogen are participating in the demonstration. Nel is one of several manufacturers of modular electrolyzers. Others include US-based Plug Power, Germany's Siemens, and Canada's Hydrogenics.

Scot Greenlee, Exelon's senior vice president of engineering and technical industry support, said the company concluded after a two-year study that, second only to steam heat for greenhouses in the marijuana-growing industry, hydrogen production was the most lucrative alternative use for nuclear plants. Potential industrial uses of hydrogen include petroleum refining, steelmaking, chemical synthesis, and, in combination with carbon dioxide captured from corn ethanol production, synthetic fuels.

Separately, Energy Harbor, an Ohio utility company, is set to install a 2 MW electrolyzer at its Davis-Besse Nuclear Power Station near Toledo. Project manager Alan Scheanwald said the equipment will be installed during the plant's next refueling outage in March 2022. Partners in the demonstration are Xcel Energy, which owns three reactors at two sites, and Arizona Public Service, which operates three reactors at the Palo Verde plant, the US nuclear industry's largest installation. DOE is providing $9.2 million of the project's $11.5 million cost. The hydrogen generated will be sold for off-site use.

Energy Harbor will operate its electrolyzer for six to eight months to determine whether there is a business case to scale up production. "We definitely see hydrogen as an emerging technology and a growing market," Scheanwald said.

Green, Greenlee, and Scheanwald all spoke during an 8 June virtual conference sponsored by the American Nuclear Society (ANS).

Nuclear industry woes

Nearly all US hydrogen is currently produced through a process called steam reforming, in which a nickel-catalyzed reaction between methane and steam at 700–1100 °C generates hydrogen and CO_2. According to the International Energy Agency (IEA), the cost of steam reforming in the US was around $1/kg in 2018. Last August Idaho National Laboratory published a study titled *Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest*. In it, the lab reported that an unidentified

A 2 MW ELECTROLYSIS PLANT IN FALKENHAGEN, GERMANY, built by Hydrogenics. A similar-sized demonstration plant is slated to be installed at the Davis-Besse Nuclear Power Station near Toledo, Ohio, with support from the Department of Energy.

reactor in the Midwest could produce hydrogen by electrolysis at a cost of \$1.50/kg—well below the \$2/kg target for carbon-free production set by DOE for 2020. But the lab's estimate was highly qualified; it assumed that states would grant clean-energy credits to nuclear plants and that the cost of electrolyzers would decrease substantially. Several states, including Illinois, New Jersey, and New York, already provide clean-energy credits to some of the nation's 96 reactors to help them compete in the wholesale electric markets.

The current capital cost of electrolyzers is \$1000 to \$1500 per kilowatt, according to industry and IEA reports. The IEA and DOE have projected that capital cost can be lowered to \$400/kW, a point at which continuous but not intermittent electrolysis could be economically competitive with steam reforming, says Sunita Satyapal, director of DOE's hydrogen and fuel cell technologies office. Reaching that lowered cost will require increasing electrolyzers' efficiency to 70% from the current 60% and improving their durability.

Because nuclear-powered electrolyzers would be operated nearly continuously, their levelized cost of production—the lifetime cost divided by hydrogen output, a standard measure for comparing production methods—should be much lower than that for electrolysis powered by intermittent wind and solar energy.

On 22 June DOE announced a five-year, \$50 million initiative on electrolyzer R&D that will be carried out by a consortium of national laboratories. The scope includes basic and applied research on materials, materials integration, and manufacturability. Industry and academia are expected to partner with the labs and bring in additional funding, Satyapal says.

US hydrogen production is forecast to nearly double to 25 million tons a year by 2030, according to Greenlee. The 13 million tons produced annually now would require power plants having a total capacity of 74 GW of electricity if it were generated by electrolysis, Greenlee said. A typical nuclear reactor has a capacity of around 1 GW.

A DOE request for proposals that closed 30 June offered \$64 million for R&D on a variety of hydrogen topics, including \$15 million for improving high-volume manufacturing of megawatt- and gigawatt-scale electrolyzers. Winners will be selected in the next several months.

The efficiency of electrolysis is boosted considerably at elevated temperatures, and nuclear reactors could supply the heat. Today's light-water reactors can provide steam at up to 300 °C, according to the World Nuclear Association. Operation at 800 °C or higher can raise efficiency above 90%, Satyapal says. Advanced reactors, if they become a commercial reality, could supply such temperatures.

Xcel Energy, a partner in the Energy Harbor project, is proposing to demonstrate a high-temperature electrolyzer, most likely at its Prairie Island nuclear plant, said Patrick Burke, the company's vice president of nuclear strategy. "We are big believers in generating hydrogen from nuclear power, but we have to prove it can be supplied at utility scale."

In Minnesota, where Xcel's reactors are located, potential regional markets for hydrogen include oil refineries and producers of ammonia and fertilizer, Burke said. Companies that operate large data centers are also interested in buying cleanly sourced electricity. Blending hydrogen into the natural gas supply system would lower that fuel's CO_2 footprint. And hydrogen can replace coal for reducing iron ore, an essential step in steelmaking. But companies will have to meet the challenges of safely storing hydrogen, create a distribution network, and deal with regulatory, siting, and licensing issues before deploying electrolysis on an industrial scale, Burke noted.

Greenlee cautioned at the ANS conference that the US nuclear industry shouldn't count on hydrogen to solve its economic crisis. "The big challenge is working with the states to get them interested in making the plants viable so we can exist long enough to see [a hydrogen economy] become a reality." It's not enough that Exelon has received state clean-energy credits for two plants in Illinois and one in New York, he said. In the region where Exelon operates, "the market construct is broken and needs to be fixed."

Big plans abroad

Outside the US, electrolysis as a carbon-free source of hydrogen has been mainly associated with renewable energy. In March a 10 MW electrolyzer began operating in Namie, northeastern Japan, using power from renewables. Hydrogenics in Canada is building what will be the world's largest proton exchange membrane (PEM) electrolyzer for Air Liquide in Bécancour, Quebec. Nearly all of that province's power comes from renewables.

In April the Australian Renewable Energy Agency launched a renewable hydrogen production project and offered AU\$70 million (\$44 million) for green electrolysis at commercial scale. The agency aims to support deployment of two or more advanced electrolyzers with a minimum capacity of 5 MW and preferably at least 10 MW. Each electrolyzer must be powered by renewable electricity, either directly or through renewable-power purchase agreements. Australia's national hydrogen strategy, unveiled in November 2019, sets a goal of AU\$2/kg for green hydrogen (see PHYSICS TODAY, May 2019, page 28). Australia has no nuclear power.

French nuclear giant EDF formed a new subsidiary, Hynamics, in 2019; the move signaled the utility company's intent to become a major player in green electrolysis for industrial and transportation applications. A study commissioned by EDF last year confirmed the feasibility of installing two 1 MW electrolyzers at one of the eight nuclear power stations the company operates in the UK. The two electrolyzers would employ different approaches: PEM cells and the more common alkaline technology.

The European Union (EU) released a hydrogen strategy on 8 July that calls for 1 million tons of hydrogen to be produced from green electrolyzers by 2024, with that figure increasing to 10 million tons in 2030. The plan does not mention a role for nuclear power, but proposes "hydrogen valleys" where electrolyzers would be directly powered by local renewable sources. The EU currently produces about 10 million tons of hydrogen annually, almost all from natural gas. Notably, the EU plan acknowledges that methane reforming will continue to supply part of Europe's hydrogen demand, but those plants will be required to capture and store their CO_2 emissions.

Germany has its own national green hydrogen initiative, funded at €7 billion (\$7.9 billion). Nuclear power won't be included: The last of Germany's nuclear plants is to be closed by 2022. The plan calls for 5 GW of domestic hydrogen production from renewable sources to demonstrate feasibility at scale, but beyond that, Germany will count on other parts of the globe to provide the massive amounts of renewable energy it will need to satisfy its hydrogen goals. **David Kramer**