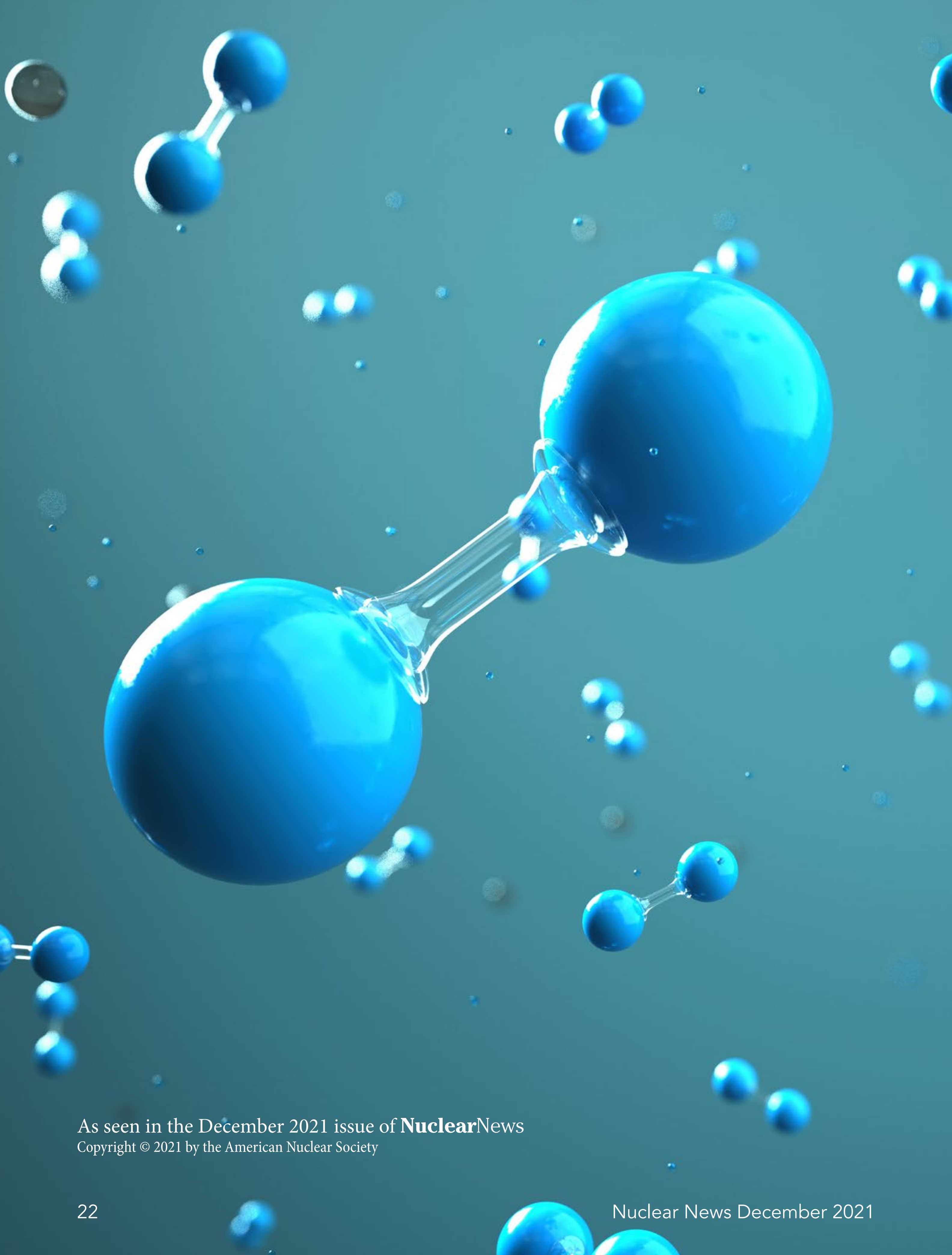

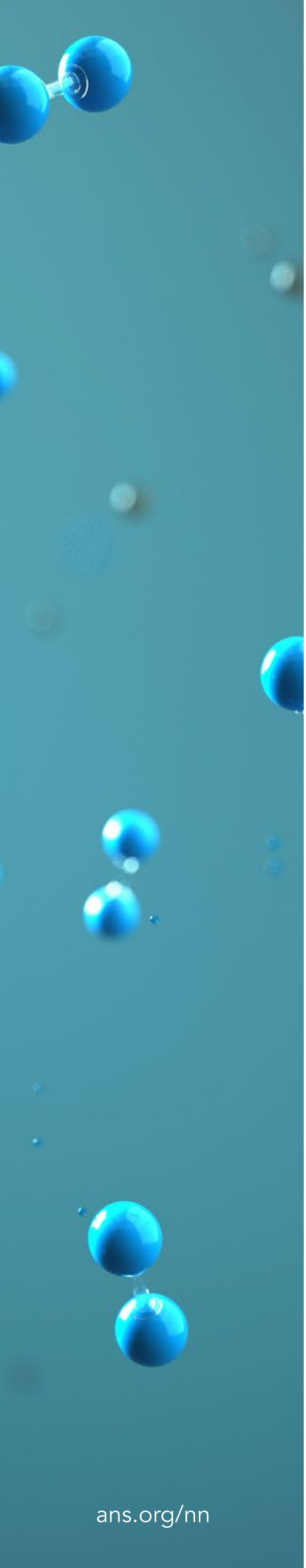

Hydrogen:

The best shot for nuclear sustainability?

By Susan Gallier

Nuclear power plants are not quick to change. So when four utilities announce they will make room for shiny new electrolyzers and consider tweaking their business model, that's news.

Nuclear power plants can leverage the energy stored in some of the world's heaviest elements to generate the lightest: hydrogen. That is not news, but it casts an aura of alchemy over straightforward engineering. Amid the hype, and the hope of significant federal funding, it's worth acknowledging that hydrogen has an industrial history over 100 years old. In the potential matchup of hydrogen and nuclear power, it's nuclear that would be the newcomer.

Making H_2

While hydrogen accounts for about 75 percent of all matter in the universe, it's not easy to produce molecules of pure hydrogen (H_2). About 95 percent of the world's supply is made using steam reforming of natural gas (methane). For every ton of methane used, three or more tons of carbon dioxide are produced and either vented to the atmosphere—producing so-called "gray" hydrogen—or trapped, through carbon capture and sequestration technology, earning its product the label "blue" hydrogen. With over 10 million metric tons of hydrogen produced in the United States every year, that's a lot of CO_2 to be released or stored.

"Green" hydrogen alternatives include electrolysis powered by low-carbon sources like nuclear power, which can split H_2O into its constituents using electricity in the case of low-temperature electrolysis (LTE) or both electricity and steam as inputs for high-temperature electrolysis (HTE). While LTE is a proven technology, HTE promises greater efficiency when paired with light water reactors. High-temperature advanced reactors could go further by eliminating the need for electricity in favor of a thermochemical process that requires heat on the order of 800°C, along with water and recyclable chemical catalysts.

"Advanced reactors can provide us with high-temperature heat to produce hydrogen very efficiently," said Shannon Bragg-Sitton, director of the Integrated Energy and Storage Systems (IES) Division at Idaho National Laboratory, speaking before the Senate Committee on Energy and Natural Resources in November. "Using that high-temperature heat and electricity we can produce hydrogen approximately 30 to 50 percent more efficiently than just using electricity alone."

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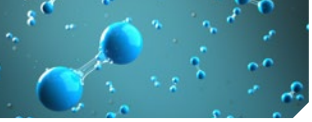
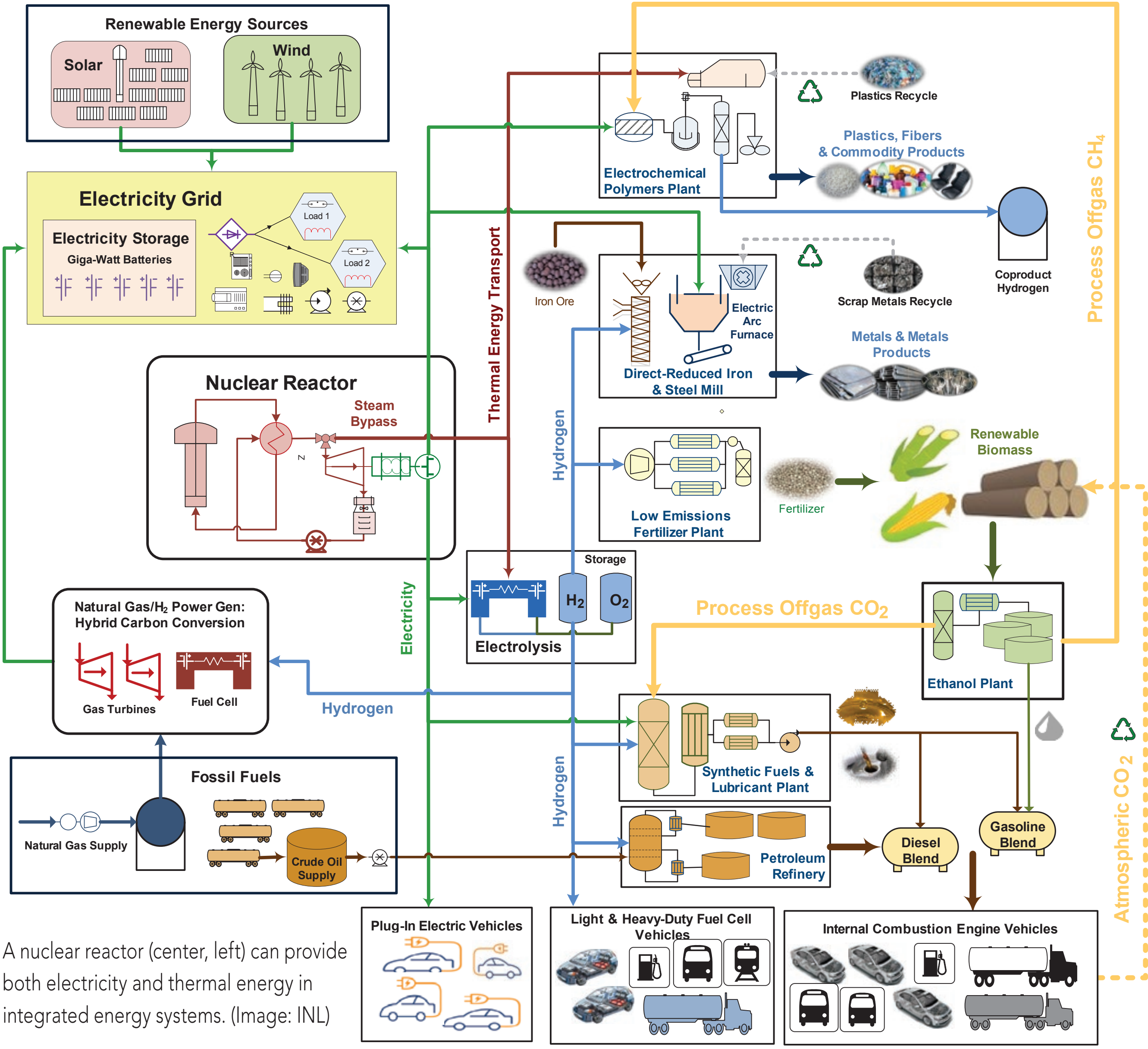




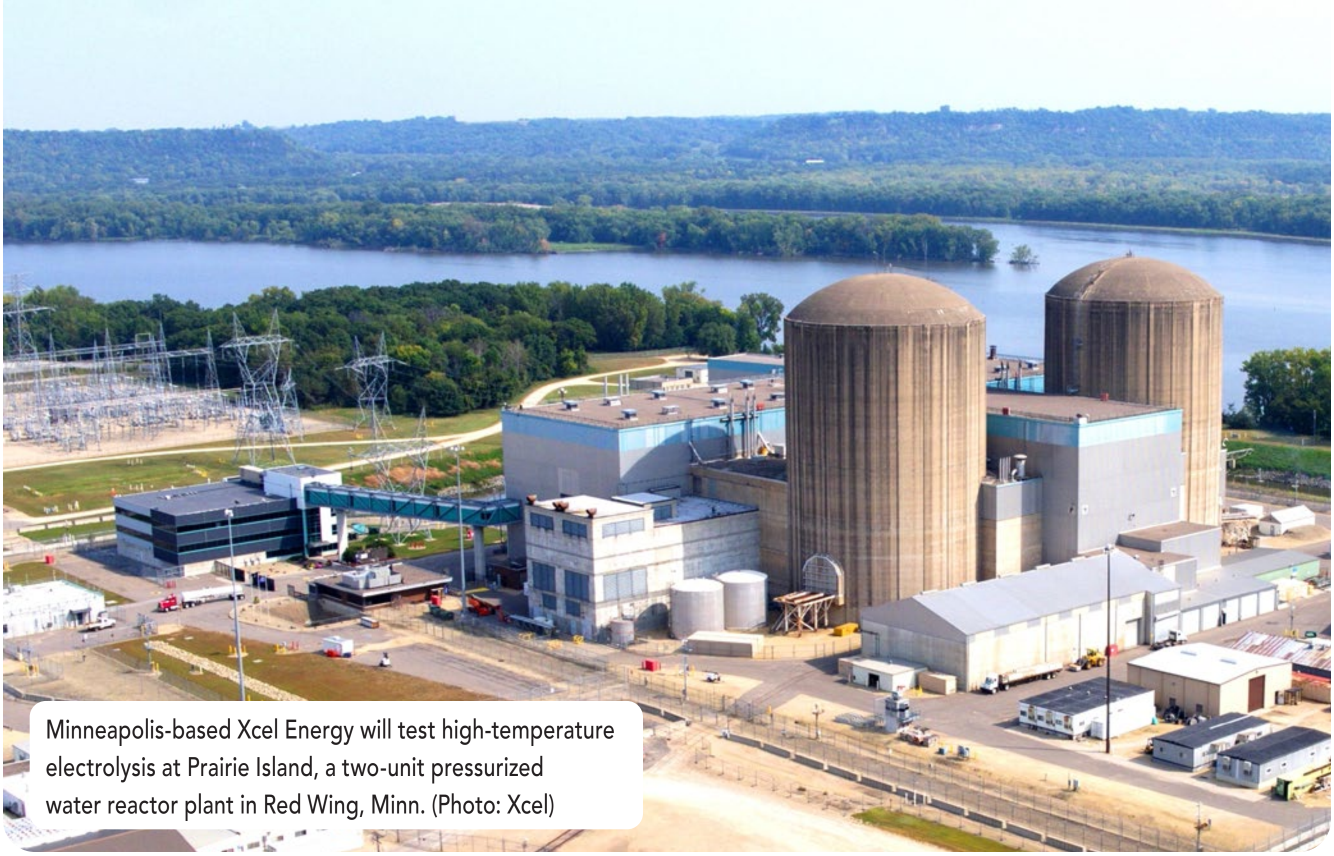
A nuclear reactor (center, left) can provide both electricity and thermal energy in integrated energy systems. (Image: INL)

Electricity economics

U.S. nuclear power plants were built for baseload electricity generation. Alternative uses, including hydrogen production, are only being considered because the grid has become less hospitable. “What happened is the price of natural gas collapsed, which collapsed the price of electricity,” explained Charles Forsberg, principal investigator for fluoride salt–cooled high-temperature reactor research at the Massachusetts Institute of Technology. “Before natural gas showed up, why would you turn an LWR to producing hydrogen?”

Now utilities are increasingly willing to consider those alternatives. The ANS Utility Working Conference held this past August included two days of conversation about the operational and design impacts and regulatory implications of producing hydrogen at nuclear plants in an educational track on Alternate Revenue Streams.

“It’s about trying to open our eyes to the possibility that maybe we’re going to do something different than just generate electricity for the whole life of the plant,” said Jack Cadogan during the first session in the track. Cadogan retired about a year ago from Arizona Public Service (APS), after stints as site vice president and engineering vice president at the Palo Verde plant, and is now working as a consultant. “We’re actually looking at two particular options here. Are we trying to arbitrage the energy, that is,



Minneapolis-based Xcel Energy will test high-temperature electrolysis at Prairie Island, a two-unit pressurized water reactor plant in Red Wing, Minn. (Photo: Xcel)

to store it and then put the power back on the grid? That would be one operating paradigm for the reactors, just stay in the electricity market. But we're also talking about creating hydrogen, which is a higher-value product."

Increasing solar and wind capacity also poses challenges for nuclear baseload power, and not just by lowering the price of electricity when renewable generation peaks. Load-following a nuclear plant by ramping the plant up or down can "play havoc with the plant over time," said Ken Thomas, a senior consultant for Idaho National Laboratory and a track organizer for the UWC sessions. If plants that are being asked to ramp down their power could instead divert steam and electricity to a co-located hydrogen plant, Thomas said, then even if that plant wasn't focused on maximizing income, "it gives you full asset utilization. Your reactor stays at 100 percent. . . . This is hugely important for plants to not have to play the guessing game."

Richard Boardman, who is director of the Energy and Environment Science and Technology office at INL, where he works with Bragg-Sitton, presented INL research during the UWC session, and he later represented the United States during an International Atomic Energy Agency panel discussion—"Innovations in the Production and Use of Nuclear Hydrogen for a Clean Energy Transition"—in September. Speaking to an IAEA audience, Boardman explained that "we're trying to understand how to keep the nuclear plants operating at their baseload capacity, and producing hydrogen is one way of doing that, where we switch between making electricity and sending it to the grid or producing hydrogen."

Pilots taking off

Four utilities—APS, Energy Harbor, Exelon Generation, and Xcel Energy—are prepared to test that paradigm by participating in cost-shared pilot projects through the DOE's H2@Scale program.

APS, Energy Harbor, and Xcel Energy formed a consortium to demonstrate hydrogen production in partnership with INL in 2019. Their goal, according to INL: "to improve the long-term economic competitiveness of the nuclear power industry." Energy Harbor recently announced that the 2-MW LTE skid it plans to install at the Davis-Besse plant near Toledo, Ohio, to produce commercial quantities of hydrogen will be ready for first operation in 2023. At the three-unit Palo Verde site in the Arizona desert, APS will install an LTE skid, plus 6 metric tons of storage capacity, and supply hydrogen to a nearby gas peaking plant to produce about 200 MWh of electricity during times of high demand.

Xcel Energy is the only utility with plans to draw steam as well as electricity from a nuclear plant in a test of HTE. Xcel will kick off its project at Prairie Island in Minnesota in the second quarter of 2022 and will have about two years

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to complete engineering change paperwork and install a 90 kg/day HTE skid in anticipation of producing hydrogen in late 2023 or early 2024.

Under a separate H2@Scale project, Exelon is partnering with Nel Hydrogen and three national laboratories, including INL, to install a 1-MW LTE unit at Nine Mile Point in upstate New York that will begin producing 430 kg/day to meet the boiling water reactor's turbine cooling and chemistry control needs early in 2022.

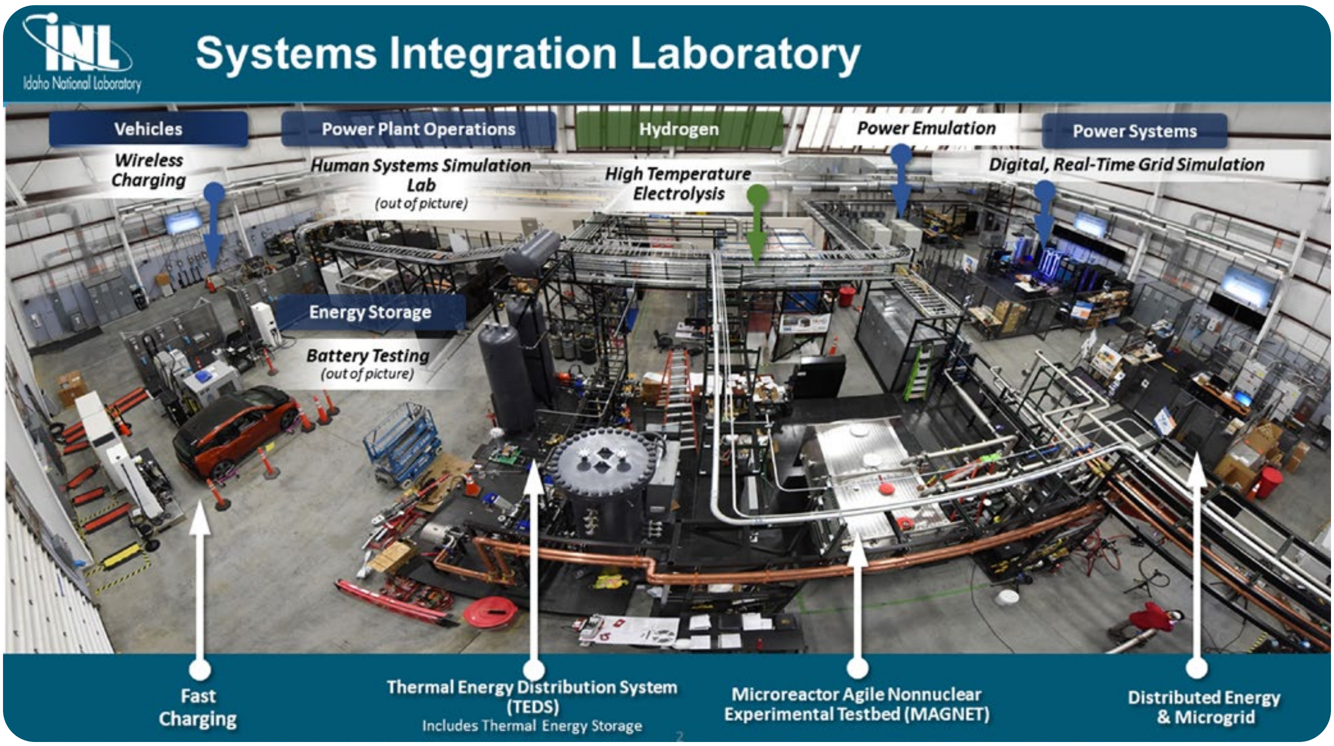
Researchers at INL and other national laboratories working in the IES program and the Light Water Reactor Sustainability (LWRS) Flexible Plant Operation and Generation (FPOG) pathway have employed software modeling to confirm that these demonstrations have economic potential. As the demos get underway, technical research is accelerating in INL's Dynamic Energy Transport and Integration Laboratory (DETAIL), where, as Boardman told his IAEA audience, "we're working on the ability to show that we can not only move between electricity production and hydrogen as demand response units, but now also to help manage the grid quality of electricity, adjusting the frequency." A full-scope simulator is demonstrating the dispatch of thermal and electrical power to a hydrogen plant, and electrolyzers featuring different technologies are also being put to the test.

No shortage of customers

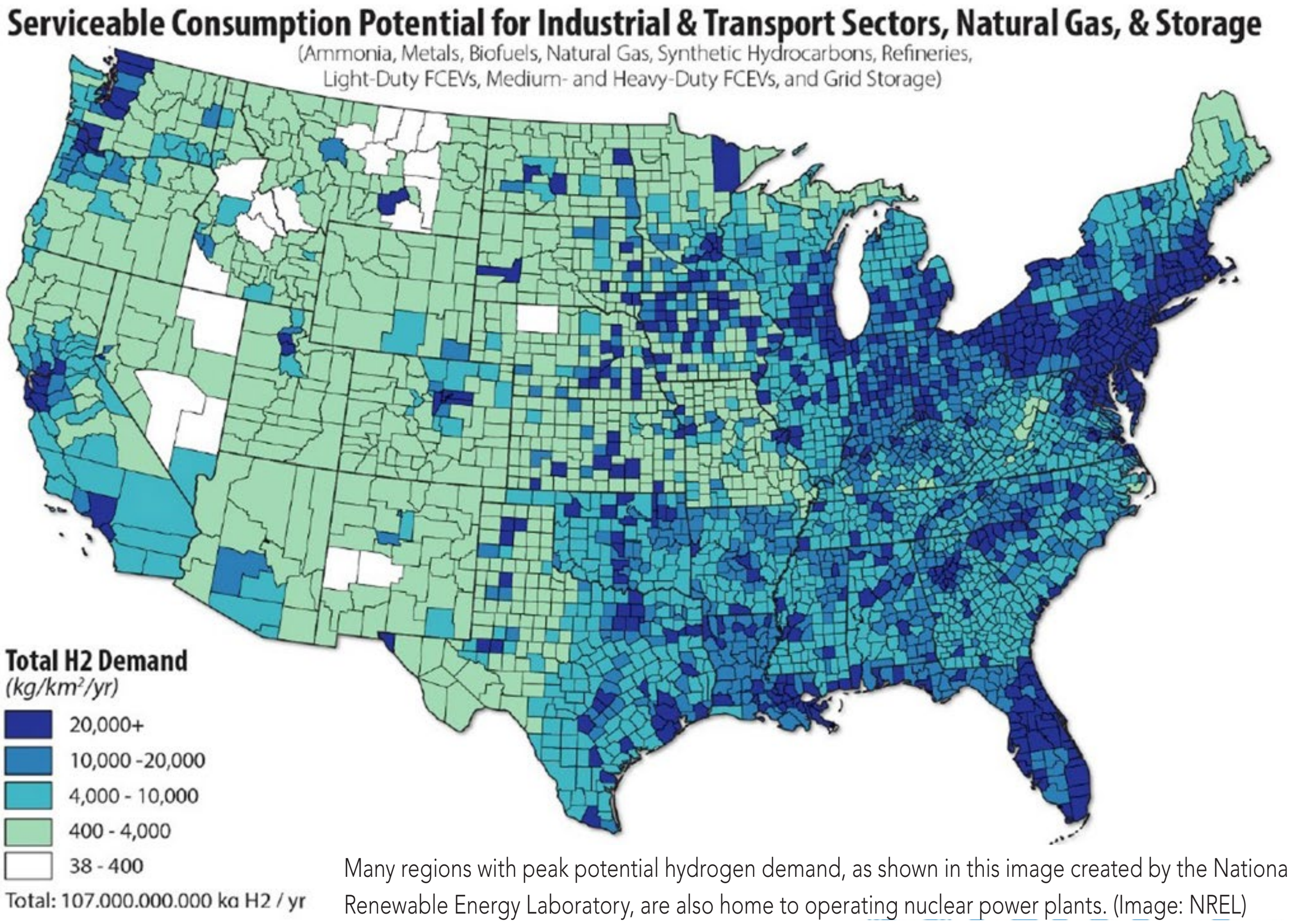
Hydrogen could account for between 10 and 30 percent of the total energy consumption in the United States by 2050, according to Forsberg. Because of hydrogen's chemical characteristics and its potential as an energy carrier, "you very quickly come to the conclusion that the minimum hydrogen market is probably going to be about 10 percent of the total global energy market," he asserted, "and that's before you get into the big heat markets like homes and producing peak electricity. There's no shortage of customers out there if you can get hydrogen to their doorstep at the right price."

Industries that need to incorporate hydrogen into chemical processes and compounds have no choice but to make or purchase a supply. Hydrogen's primary use today is at petrochemical plants, converting heavy crude oils to gasoline and diesel fuel. Hydrogen is required to produce ammonia—a critical fertilizer and the second-most-manufactured chemical in the world today—and synthetic fuels that could be used for air transportation and other sectors that are hard to decarbonize.

Hydrogen can be blended into existing natural gas networks or burned in internal combustion engines and is also a feedstock for steel production. Hydrogen fuel cells



When components in INL's Systems Integration Laboratory are connected in an integrated energy system, they comprise the Dynamic Energy Technology and Integration Laboratory (DETAIL).



Many regions with peak potential hydrogen demand, as shown in this image created by the National Renewable Energy Laboratory, are also home to operating nuclear power plants. (Image: NREL)

could provide electricity at the point of use—as backup energy for emergencies or critical facilities, or to push electricity to the grid or another dedicated application, or for light- or heavy-duty transport.

Boardman has worked at INL to connect nuclear power with the process industries for 30 years, but he is a chemical engineer by training who previously worked for U.S. petroleum and steel companies. When it comes to LWRs, he explained to his IAEA audience that "our interest is producing hydrogen and putting it into the gas pipelines or into new hydrogen pipelines so that it can go directly to industry." Boardman noted significant existing hydrogen pipelines along the Gulf Coast, near refineries, as well as "a hydrogen pipeline in the upper Midwest beneath Lake Erie that services some of the large industries in the center of our country."

Boardman added, "We're really now bringing about technical and economic assessments to make the business case for doing this. We're not only working with the petrochemical industry but beginning to have good conversations with the ammonia industry and the steel industry in the United States."

More markets could be reached with smaller advanced reactors still in development. "We see an opportunity to embed them more in industries now—to put a nuclear reactor down at the site at a petroleum refinery or near a petrochemical company. And yes, we are working with some of those companies in the United States," Boardman said, adding, "I wouldn't be able to disclose publicly, but we have a few million dollars of research going on at this time where we're looking at putting these small- to medium-sized reactors right within industry where they could be dedicated to making hydrogen."

The price of hydrogen

Clean hydrogen—whether produced from electricity derived from renewable sources, from nuclear power, or from steam methane reforming with effective carbon capture and sequestration—is currently about $5/kg. The DOE wants to see the price of clean hydrogen drop by 80 percent, to $1/kg, in 10 years, which would bring it close to current prices of gray hydrogen. Energy secretary Jennifer

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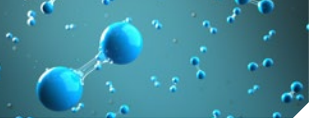

Granholm announced the "Hydrogen Shot" goal on June 7 as the first of several planned "Energy Earthshots."

In his IAEA presentation, Boardman explained a stepwise path developed by INL that could bring nuclear hydrogen to $1/kg, by improving electrolysis stacks and reducing balance-of-plant costs, by continuing to reduce LWR power production costs through LWRS program efforts, and finally by selling the oxygen that would be generated through electrolysis.

Hydrogen plants—like nuclear plants—are capital intensive and need to run at high capacity factors. "The bottom line is, if you don't run the hydrogen plant many hours a year, it's incredibly expensive hydrogen. And that's because hydrogen plants are really expensive. They're like nuclear plants. You can't run it 'a bit,'" Forsberg said. "If you're in the hydrogen business, you should think about a business model where you're producing hydrogen 70 or 80 percent of the year, and the only time you shut it down is when the price of electricity is high."

"It's not about 'Can you make hydrogen?' as much as 'Can you actually install it through all of the different regulatory codes and standards?' If you can actually make it happen, then you can think about what's next."

On site: Integration and regulation

Xcel Energy's Prairie Island will house the smallest of the four nuclear plant demos, but as the only site that will use HTE, it is also the most complex, requiring steam as well as electricity and clean water.

Molly Strasser, manager for nuclear innovation engineering at Xcel, explained that "with a pilot, it's a pretty small amount of steam and electricity, kilowatt size versus megawatt size. That story changes if we're looking for larger-scale-product projects, but we're focused really on implementation of the pilot first." Xcel plans to send data from operation of the unit both to the electrolyzer vendor and to INL.

"Prairie Island has some existing infrastructure that provides access to steam outside the turbine building, so we're taking advantage of that existing infrastructure to install the pilot," Strasser said. "We're still working through the power for the electrical source, and that will be something that will go through the engineering change process that kicks off early next year."

While a ready supply of water is available at Prairie Island, water supply could be a bottleneck for the expansion of some projects, Boardman pointed out in August at the UWC. He put some numbers to it, explaining that HTE requires purified water "at about one flush of the toilet for 1 kilogram of hydrogen" and saying that if a full-size LWR was to scale up to making about 600 metric tons per day, it would need about 1 million gallons of water.

Xcel expects to be able to use the engineering change process under 10 CFR 50.59 for the Prairie Island pilot. "One of our primary purposes is to demonstrate that we can actually install an electrolyzer at a nuclear power site," said Patrick Burke, the company's vice president of nuclear strategy. "It's not about 'Can you make hydrogen?' as much as 'Can you actually install it through all of the different regulatory codes and standards?' If you can actually make it happen, then you can think about what's next."

Other utilities will be watching as that regulatory process unfolds. Boardman told his IAEA audience on September 21, "Just last week I held a meeting with over 85 participants from the U.S. utilities, and we've determined that it will be in our interest to set up two important stakeholder groups." A hydrogen regulatory group would “work toward being able to permit these large hydrogen plants in proximity of the nuclear plants,” while “a second group is working on how we will actually engineer and tap into the thermal energy systems of these light water reactors, taking large amounts of thermal energy out to support the hydrogen production.”

The H2@Scale participants are already looking ahead to larger projects. At Energy Harbor’s Davis-Besse, “They’re already making engineering changes to their switchyard, which will allow us to scale up to hundreds of megawatts,” Boardman said. “So that’s the goal and the vision. We have the end state in mind—not just these small demonstration projects . . . we’re really interested in scaling them up.”

Hydrogen hubs: 50 years in the making?

Stephen J. Gage and David G. Jopling published an article—“Nuplex potential in the South”—in the November 1971 issue of *Nuclear News*. The Nuplex concept was popularized by Atomic Energy Commission chairman Glenn Seaborg and described by Gage and Jopling as “an energy center surrounded by power-intensive chemical, metallurgical, and agricultural industries sited to utilize low-cost electricity, steam, and water produced with a nuclear reactor and organized to create synergistic relations in raw materials and energy flows between the separate processes.”

Even 50 years ago, Gage and Jopling acknowledged that no new knowledge or techniques were needed; instead, “the potential impact of low-cost power for the clustering of interrelated industries and/or intensive agriculture as opposed to the development of such industries at dispersed sites constitutes the energy center’s innovation.” The authors described Nuplex studies carried out by Oak Ridge National Laboratory and potential deployments in Texas and Puerto Rico, and they concluded that “the challenge of the Nuplex concept has become a matter of timing—a question of *when* rather than *whether*.”

Could the time be now? On October 8, the DOE announced that it intended to issue a funding opportunity to analyze the potential for streamlined regional clean hydrogen deployments, co-locating clean hydrogen supply and demand in specific regions in pursuit of the DOE’s cost-reduction Hydrogen Shot. Funding may depend on congressional action that is still pending at this writing.

Xcel is open to possibilities in Minnesota. “We are aware of some of the proposed legislation, with the DOE building hydrogen hubs around the country,” Burke said. “We’re looking at that to see if that might be an option for us. We’re staying informed of those possibilities, but we haven’t made any commitments.”

The path ahead

“How soon are we going to get it done?” Boardman asked rhetorically at the UWC, as he displayed a slide forecasting the potential for gigawatt-scale hydrogen plants by 2030, powered by 20–30 LWRs and producing 2–5 million metric tons of hydrogen per year and 2–4 million metric tons of ethylene per year while sending 5 GWt to industrial parks. “Can we get 20 to 30 plants converted over to hydrogen in a decade? We can if we stay on this path, and the demonstration projects could get us on this path.”

Those 20–30 plants are the at-risk plants under pressure from market forces today. For them, the Hydrogen Shot may turn out to be the best shot for nuclear sustainability.

Susan Gallier is a Nuclear News *staff writer focusing on nuclear technology research and applications.*