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PATHWAYS FOR SUSTAINABLE HYDROGEN

Ready-now blue hydrogen leads the way to decarbonization

Technical and economic pathways for sustainable hydrogen production

BLUE HYDROGEN PRODUCTION

Increasing blue hydrogen production affordability

Emissions-free production of blue H_2 for efficient transportation and decarbonization

CHEMICAL AND FERTILIZER PRODUCTION

Metallurgical damage mechanisms affecting equipment in the ammonia industry

Gulf Energy


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SPECIAL FOCUS: PATHWAYS FOR SUSTAINABLE HYDROGEN

BLUE HYDROGEN PRODUCTION

CHEMICAL AND FERTILIZER PRODUCTION

Cover Image: The Fukushima Hydrogen Energy Research Field (FH2R) in Japan can produce as much as 100 kg/hr of H_2 from a 10-MW electrolyzer, using solar energy. Photo courtesy of New Energy and Industrial Technology Development Organization (NEDO).

DEPARTMENTS

COLUMNS

EDITORIAL COMMENT

Creating pathways for sustainable H_2 production and use

A. BLUME,
Editor-in-Chief

In creating pathways for sustainable hydrogen, technology strategies and government subsidies for low-carbon H_2 production and use are of paramount importance. In the case of fossil-produced (gray and blue) H_2, carbon-capture methods are necessary retrofits or design elements of the methane reforming and coal gasification processes to reduce CO_2 emissions.

In the case of electrolyzer-produced (green) H_2, the use of renewable electricity to power the process makes it inherently low-carbon and free of direct emissions. However, when the total carbon emissions associated with the construction of renewable energy facilities and H_2 transportation and storage are taken into account, even green H_2 can be said to have a small carbon footprint. The concept of "sustainability" must be carefully defined, and projects to produce "carbon-neutral" energy must consider relevant associated emissions sources, to calculate the true carbon footprint of clean energy.

H_2 is anticipated to play a growing role in decarbonizing a range of sectors where it is difficult to reduce CO_2 emissions: long-haul and heavy road transport, marine shipping, aviation, and the production of chemicals, plastics, cement, iron and steel. At present, blue H_2 is the cheapest option for decarbonizing heat in heavy industry, but this may not be the case for long.

Much research is ongoing to make green H_2 a more affordable option, and technology breakthroughs are happening at a rapid pace. Fast development of electrolyzer supply chains are reducing prices for the equipment to 30%–50% lower than expected, and renewable energy costs have been revised 15% lower over the short term. These and other factors will combine to bring the cost of green H_2 production from around \$4/kg–\$5.50/kg at present to an estimated \$1.50/kg by 2050, with green H_2 becoming cheaper than gray H_2 (at \$1.59/kg) in optimal locations by 2030 (**FIG. 1**). Adding a carbon tax to gray H_2 production would bring green H_2 to price parity by 2030.

Momentum is building for the H_2 economy. More than 30 countries now have a national H_2 strategy and funding in place, and more than 380 active and operating carbon-neutral and low-carbon H_2 production and use projects are in development or operation around the world. By 2030, an estimated 6.7 MMtpy of H_2 production capacity will be in operation—two-thirds of which have been announced over the past year alone.

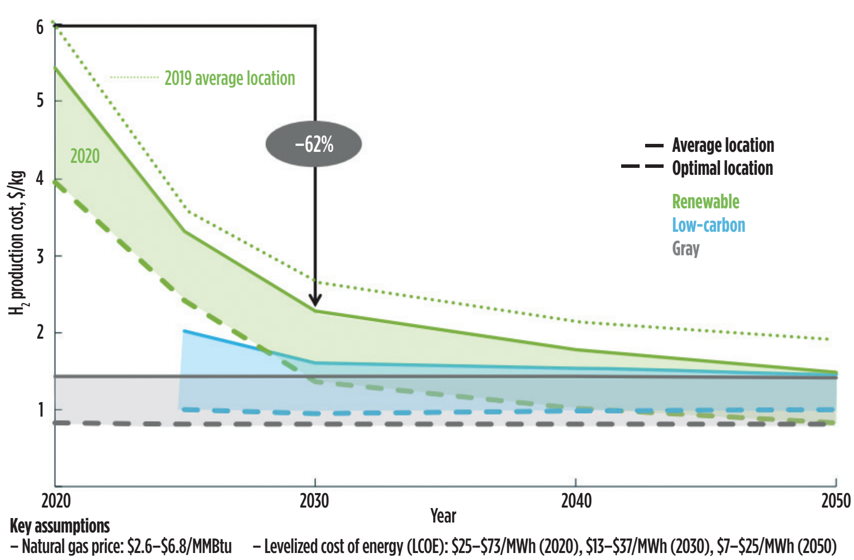

FIG. 1. Projected H_2 production costs by production pathway. Source: Hydrogen Council.

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PRODUCTION TECHNOLOGY

C-Zero gets boost for turquoise H_2 technology

C-Zero Inc. has raised $11.5 MM in funding to accelerate the first commercial-scale deployment of its drop-in decarbonization technology. The technology allows industrial natural gas consumers to avoid producing CO_2 in applications like electrical generation, process heating and the production of commodity chemicals like H_2 and ammonia.

C-Zero's technology uses thermocatalysis to split methane into H_2 and solid carbon via methane pyrolysis. The H_2 can be used to help decarbonize a wide array of existing applications, including H_2 production for FCEVs, while the carbon can be permanently sequestered. When renewable natural gas is used as the feedstock, C-Zero's technology can even be carbon negative, effectively extracting CO_2 from the atmosphere and permanently storing it in the form of high-density solid carbon.

Proton Technologies targets 1,000 tpd of white H_2

Proton Technologies began separating H_2 in late February at its project in Saskatchewan, Canada. The company's new separation unit is for multi-year H_2 filter longevity and iteration testing, with H_2 truck loading expected later this year. Liquid O_2 is scheduled to be trucked in for injection at modest but still commercial scale. At the demonstration site, production is expected to reach 1,000 tpd of H_2 after the construction of a large air separation unit.

Proton's technology is said to produce "white" H_2 at an anticipated production cost of less than $0.30/kg, with a lower carbon intensity than renewable energy. Proton's process involves injecting O_2 into spent oilfields. This triggers reactions that produce H_2. A proprietary downhole filter allows only H_2 to come into the production well and up to the surface, leaving the carbon in the ground. The cost structure is low because late-life oilfields, which already contain decades of fuel, serve as the reaction vessel.

UEDC technology to produce low-cost green H_2 in Arizona

United Energies Development Corp. (UEDC) is constructing a patented photovoltaic (PV) and electrolyzer hybrid facility in Arizona, using classified technology originally designed for NASA. The patented process uses ultra-pure groundwater to produce 99.9998% pure H_2 and O_2 gas, using specialized equipment and a large PV array.

At present, all H_2 comes into Arizona by tanker or rail from California. The new facility will eliminate this transport cost, bringing H_2 production costs to $1.33 kg/$H_2$ at an electricity cost of $0.05/kWh. UEDC's equipment uses only 1.2 MW/hr to make 1,077 kg/H_2 per day. UEDC will store both solar and off-peak electricity at night, and sell it back to the utility when it is required by regulatory agencies or when utilities are at capacity.

Catalyst improves H_2 production efficiency from SMR

Magma Catalysts' Magcat Textured catalyst allows for CO_2 reductions from the steam methane reforming (SMR) process on the order of 10%–15%, mainly due to improvements to heat transfer in the reaction zone, which helps produce H_2 more efficiently and sustainably.

The heat transfer improvement provides high intrinsic strength and lower pressure drop across the process. These properties deliver performance benefits at a constant plant rate, including lower pressure drop, lower tube skin temperatures and reduced reformer firing.

The catalyst is commercialized and is being used at two top refineries in the U.S. and a major industrial gas company, among others, as the early adopters of the technology.

H2Pro wins $22 MM in funding for alternative electrolysis technology

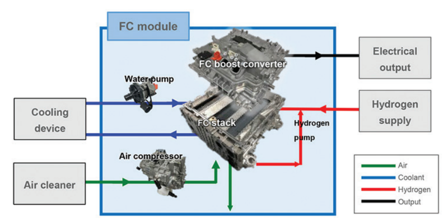
The Israeli company has secured $22 MM in funding for its water-splitting technology that could produce green H_2 at a cost of $1/kg by the second half of the decade—an ambitious price level that is not expected to be achieved until mid-century.

The company's technology is claimed to operate at 95% efficiency and higher pressure, and cost significantly less than existing electrolysis technologies. The funding will help H2Pro take its technology from lab scale to larger scale, at a production rate of 1 kgd.

The technology is similar to alkaline electrolysis, although it uses renewable electricity to break apart H_2 and O_2 atoms, as well as to pair two H_2 atoms and two O_2 atoms, respectively, to make separate gases. Energy use is reduced by splitting the step in two. First, H_2 is created at the electrolyzer cathode. The reaction also changes the composition of the anode (Ni). The cell is then flooded with hot liquid, and the anode releases O_2 gas via thermal energy, before the first step is performed again.

TRANSPORTATION/ MOBILITY

Toyota develops fuel cell system for H_2 FCEVs



Toyota Motor Corp. has developed a product that packages a fuel cell system into a compact module. The new module can be utilized by companies that are developing and manufacturing fuel cell products for a wide variety of applications, including mobility such as trucks, buses, trains and ships, as well as stationary generators.

In addition to its effort to popularize FCEVs, Toyota will continue to strengthen its initiatives as a fuel cell system supplier to promote H_2 utilization, with the aim of reducing CO_2 emissions. The company has been taking various initiatives toward the creation of an H_2 society, such as selling the Mirai FCEV and the Sora FCEV bus, selling fuel cell systems to fuel cell product companies, and allowing royalty-free use of its FCEV-related patent licenses.

Toyota has developed a product that packages individual fuel cell system-related products of the second-generation Mirai with enhanced performance, such as the fuel cell stack, as well as components that handle air supply, H_2 supply, cooling and power control, into a single compact module. For more information on FCEV and fueling network developments in Asia-Pacific, see this issue's Regional Report.

NICE, SARTA demo liquid H_2 pump technology for buses

NICE America Research (NICE), the U.S. R&D division of China Energy, and the Stark Area Regional Transit Authority (SARTA) are conducting a demonstration project of NICE's submerged liquid H_2 pump technology at the transit system's Canton, Ohio headquarters.

The NICE system will be used to refuel SARTA's H_2 fuel cell-powered fleet of full-size buses and paratransit vehicles. The testing period will enable NICE and SARTA to evaluate the performance and reliability of the refueling system in real-world transit agency operating conditions. During previous field tests, the pump pressurized and delivered precooled, compressed gas at flowrates greater than 200 kg/hr for 35-MPa refueling applications, using delivery profiles consistent with the J2601-2 standard.

NICE's liquid pump is said to significantly reduce energy demand from H_2 compression and simplify station design, which will lead to reduced costs and increased flexibility for operators of H_2-powered vehicles.

Ballard sees more orders for FECV bus fuel cells

Ballard Power Systems received purchase orders from Solaris Bus & Coach for 10 Ballard FCmove fuel cell modules to power 10 Solaris Urbino-12 H_2-powered buses in the Province of Gelderland, the Netherlands.

The buses will replace diesel buses currently in service and are expected to cumulatively travel more than 1 MMkm/yr (620,000 mi/yr). Each of the single-decker H_2 buses is 12 m (40 ft) long and is capable of traveling 350 km (210 mi) on a single H_2 refueling.

With the deployment of the 10 buses, Ballard modules will be powering a total of 67 Solaris buses in the Netherlands, Germany and Italy. The follow-on order is indicative of the growing European and global adoption of zero-emissions FCEVs.

Ballard's FCmove fuel cell module is also powering the first-ever fuel cell bus manufactured in New Zealand by Global Bus Ventures.

Loop Energy to provide fuel cells for heavy-duty trucking

Loop Energy and Rheintal-Transporte have signed an agreement for the development and supply of heavy-duty H_2 fuel cell range-extension solutions for battery electric trucks in Europe.

As part of the agreement, Germany-based Rheintal will use Loop's eFlow fuel cell modules to expand driving range capabilities of battery electric trucks to the levels required by its fleet of long-haul, cold-chain logistics vehicles. Rheintal anticipates orders of eFlow fuel cell modules for more than 20 zero-emissions H_2 trucks and trailers over the next 24 months. Rheintal's evolution to H_2 fuel cell electric freight transport aligns with its goal of enabling emissions-free customer transport deliveries before 2030.

In addition to the supply of Loop Energy fuel cell products, the agreement provides Rheintal with full access to Loop's end-to-end technical support, as well as access to a network of prequalified channel partners specializing in H_2 electric power train design, supply of subsystem components and H_2 fuel infrastructure.

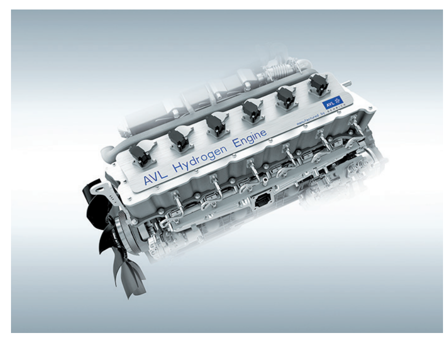
CAeS to develop H_2 fuel cell aircraft

Cranfield Aerospace Solutions (CAeS) will use recent advances in H_2 fuel cell technology to develop a commercially viable, retrofit powertrain solution for the nine-passenger Britten-Norman Islander aircraft.

Project Fresson will deliver an emissions-free, H_2 fuel cell-powered flying demonstrator by September 2022. Having completed a comprehensive evaluation of technologies and configurations for sustainable aircraft propulsion, the Fresson team concluded that H_2 fuel cell technology is the optimum solution to meet environmental, regulatory and operational requirements for this size of aircraft, enabling zero carbon emissions and reducing operating costs.

Project Fresson is supported by the ATI Program, a joint government and industry investment to maintain and grow the UK's competitive position in civil aerospace design and manufacture. The program, delivered through a partnership between the Aerospace Technology Institute (ATI), Department for Business, Energy and Industrial Strategy (BEIS) and Innovate UK, addresses technology, capability and supply chain challenges.

AVL advances H_2 internal combustion engine



AVL, an independent company for the development, simulation and testing of powertrain systems, continues to develop an H_2 combustion engine of the latest generation. The engine is specifically tailored for use in heavy-duty vehicles, and it aims to reduce the mass of greenhouse gas emissions from heavy-duty vehicles exceeding 3.5 t. This will significantly reduce the CO_2 emissions attributable to these types of transport vehicles in the coming decades.

The development project's target is to increase both the efficiency potential of multi-port and direct-injected H_2 engine concepts for the direct propulsion of a commercial vehicle with an existing standard powertrain. AVL used a 12.8-l natural gas engine for the basis of development and set its performance target at 350 kW. With its development of an H_2 engine, AVL aims to reduce CO_2 emissions and also ensure high reliability of the piston-bore interface.

POWER GENERATION/ STORAGE

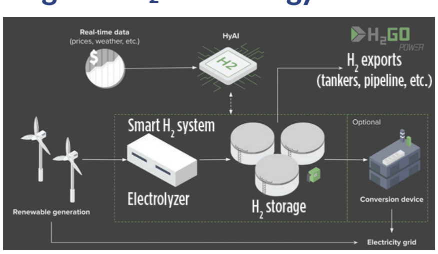
Intermountain Power, Siemens partner for H_2 storage

Intermountain Power Agency has teamed with Siemens Energy to perform a conceptual design study for integrating an H_2 energy storage system into a combined-cycle power plant. The study is designed around Siemens Energy's Silyzer technology, which uses electrolysis to generate H_2. The scope of the research includes H_2 compression, storage and intelligent plant controls.

The goal of the study, which began in March at the 840-MW Intermountain Generating Station in Delta, Utah, is to analyze the overall efficiency and reliability of CO_2-free power supply involving large-scale production and storage of H_2. The study will also analyze aspects of integrating the system into an existing power plant and transmission grid, such as the interaction with subsystems, sizing and costs.

The Intermountain Generating Station is transitioning from coal to natural gas, with plans to integrate 30% H_2 fuel at startup in 2025 and 100% H_2 by 2045. The project will provide 840 MW of electricity to customers in Utah and Southern California.

EMEC, H2GO Power trial AI green H_2 technology



H2GO Power, in collaboration with the European Marine Energy Centre (EMEC) and Imperial College London, are trialing the use of artificial intelligence (AI) software coupled with H_2 technology. The HyAI (Hydrogen AI) project is a pilot demonstration of AI software-controlled H_2 storage technology. HyAI will show how software integrated with H_2 hardware can make intelligent, data-driven asset-management decisions in real time and optimize renewable energy integration into the UK electricity grid.

Led by H2GO Power, developers of low-pressure H_2 energy storage and AI-driven asset management software, the project has integrated an innovative AI software platform with one of the company's H_2 storage units. Trialing the system using energy data supplied by EMEC from its H_2 plant in Orkney, the AI platform acts as an energy management system, integrating data about weather, electricity prices and grid management. It then translates this information, using AI predictive algorithms to optimize the operation of the storage systems by predicting future power cost and user demands.

Initial results have indicated that the AI-enabled approach can produce H_2 in a more cost-effective way, while also helping alleviate stresses on the national grid.

Phillips 66 to advance reversible SOFC technology

Phillips 66 received a $3-MM grant from the U.S. Department of Energy to advance the development of high-performance reversible solid oxide fuel cells (SOFCs). The company will collaborate with the Georgia Institute of Technology to demonstrate the commercial feasibility of a low-cost, highly efficient reversible SOFC system for H_2 and electricity generation.

Reversible SOFCs allow the fuel cells to operate in either power generation mode, as an SOFC; or reverse mode, as a solid oxide electrolysis cell (SOEC). In the latter, electricity is applied to the cells to produce H_2 through electrolysis. Phillips 66 holds eight granted U.S. patents and 22 pending U.S. patent applications in its SOFC intellectual property portfolio.

TRANSPORT/ DISTRIBUTION

Quantum Fuel Systems to provide H_2 trailers

Quantum Fuel Systems, a fully integrated alternative energy company, has been selected by Certarus Ltd. to develop and provide H_2 "virtual pipeline" trailers to be delivered by the end of 2021. The trailers are part of a $22-MM contract that includes the provision of "virtual pipeline" trailers for natural gas.

Certarus is in active discussions for several potential H_2 pilot projects in which Quantum will provide trailers to transport H_2. Quantum launched the world's first 5,000-psi H_2 system on a commercial vehicle in 1999, and later was the first to certify a 10,000-psi H_2 storage tank to international standards.

Nortegas launches H_2 injection research project

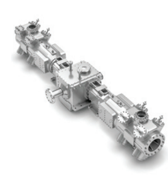
Nortegas has launched H2SAREA, a research project focused on the safe injection of H_2 into natural gas distribution infrastructures, by means of researching advanced technological solutions. The injection of renewable gas into existing natural gas distribution networks will allow Nortegas infrastructure totaling more than 8,000 km to be used.

The project consists of researching new technological solutions, equipment and components, which will allow the natural gas networks to be transformed to distribute H_2 in different blending scenarios: H_2 injection systems, compression systems, development of specific smart fixers for H_2, research into new materials and components suitable to be used in both 100% H_2 environments and in variable methane–H_2 mixes, modular H_2 separation systems, sensors, burners, etc.

The H2SAREA project will span 3 yr. In the first phase, H_2 injection will be up to 20%. Percentages will be gradually increased in a second phase up to 100% H_2. The project is part of the Basque Hydrogen Corridor, where Nortegas is working on additional initiatives to promote the H_2 economy.

TURBOMACHINERY

Burckhardt to provide compressors for H_2 liquefaction plant



Burckhardt Compression has been selected as compressor supplier for a newbuild H_2 liquefaction plant in South Korea. The order includes two fully skidded, BCS API 618 compressor packages with 136 kW and 1,800 kW power output, for the compression of H_2 within the liquefaction process.

The plant will produce 5 tpd of liquefied H_2 from 2023 to supply H_2 charging stations in South Korea.

PROJECTS UPDATE

A. BLUME, Editor-in-Chief

EUROPE

BP to build UK's largest blue H_2 plant

The company is targeting 1 GW of blue H_2 production by 2030 at its proposed H2Teesside development. The project would capture and send for storage up to 2 MMtpy of CO_2. The proposed development would contribute to the UK government's target of developing 5 GW of H_2 production by 2030.

With close proximity to North Sea storage sites, pipe corridors and existing H_2 storage and distribution capabilities, the area is well placed for H2Teesside to lead a low-carbon transformation. Industries in Teesside account for more than 5% of the UK's industrial emissions, and the region is home to five of the country's top 25 emitters.

HEAVEN project eyes emissions-free aircraft with cryogenic H_2

The High powEr density FC System for Aerial Passenger VEhicle fueled by liquid Hydrogen (HEAVEN) project consortium in Europe is participating in the rise of cryogenic H_2 and fuel cells as a mobility alternative. This technology could deliver a commercially viable airplane solution by around 2030.

Air Liquide has fine-tuned the specifications and requirements applicable to the cryogenic tank and will manufacture and test the storage in its facilities throughout 2021. H2Fly will soon finish the definitions, safety assessment and technical requirements for the safe integration of liquid H_2, the cryogenic tank and the PEM fuel cell systems (manufactured by ElringKlinger) within the aircraft.

In charge of the conceptual design of the overall architecture of the powertrain, DLR will focus on the fuel cell system development. Pipistrel is developing modifications to the demonstration aircraft to facilitate the integration of the liquid H_2 fuel tank designed by Air Liquide, ensuring that ARP and SAE AIR6464 guidelines are encompassed.

INOVYN H_2 project to support decarbonization in Norway

INOVYN plans to build a 20-MW electrolyzer to produce clean H_2 through water electrolysis, powered by zero-carbon electricity. The project will reduce at least 22,000 tpy of CO_2 by minimizing the carbon footprint of INEOS' operations in Norway and serving as a hub to provide H_2 to the Norwegian transport sector.

The proposed development will be integrated into existing assets and ties into ongoing discussions with companies to establish a network of refueling stations in Norway to provide buses, trucks and taxis with clean H_2. INOVYN aims to produce enough additional H_2 per day to fuel up to 400 buses or 1,600 taxis.

Siemens Energy, Air Liquide in large-scale electrolyzer partnership

Siemens Energy and Air Liquide intend to combine their expertise in proton exchange membrane (PEM) electrolysis technology for sustainable H_2 production. They will focus their activities on the co-creation of industrial-scale H_2 projects in collaboration with customers; mass manufacturing of electrolyzers in Europe, especially in Germany and France; and R&D activities to co-develop next-generation electrolyzer technologies.

Under the framework of their cooperation, Siemens Energy and Air Liquide will jointly apply for large-projects funding under the EU's Green Deal and the Important Project of Common European Interest (IPCEI) scheme for H_2. One such opportunity identified by the companies is the Air Liquide-H2V Normandy project in France, with a capacity of 200 MW.

EUROPE

Electrolyzer at German power plant furthers ALIGN-CCUS

Chemieanlagenbau Chemnitz (CAC) successfully completed a water electrolysis plant at the RWE power station site in Niederaussem, Bergheim, Germany, as part of the international research project ALIGN-CCUS. Under the project, 34 companies, research institutes and universities from throughout Europe are pursuing the goal of transforming six European industrial regions into economically robust centers with significantly reduced CO_2 emissions by 2025.

The plant consists of a skid-mounted electrolyzer, as well as H_2 compression and treatment units. The electrolyzer was developed by Asahi Kasei and integrated into a fully automated plant. The CO_2, obtained from an existing RWE facility, and the produced H_2 will be used to make dimethyl ether (DME), which can be converted into synthetic fuels.

Shell to expand electrolyzer capacity at Rheinland refinery

Shell will increase the capacity of the ITM Power PEM electrolysis plant from 10 MW to 100 MW, in line with the announced expansion of its German refinery. The project is an integral part of the planned transformation of the site into the Shell Energy and Chemicals Park Rheinland. Shell's partners for the electrolysis project are ITM Power, ITM Linde Electrolysis and Linde. Construction is expected to begin in 2022.

CIP eyes Europe's largest green ammonia plant

With A.P. Moller–Maersk as a collaborator, Copenhagen Infrastructure Partners (CIP) has unveiled plans for Europe's largest production facility for green ammonia. Green ammonia is a preferred fuel for future marine use.

The Power-to-X facility, located in Esbjerg on the Danish west coast, will convert power from wind turbines to green ammonia. The green ammonia produced at the facility can be utilized by the agricultural sector as green fertilizer and by the shipping industry as a sustainable green fuel.

According to CIP, the project has the potential to reduce CO_2 emissions by approximately 1.5 MMt, equivalent to permanently removing 730,000 cars from the roads. The facility is planned to start producing green ammonia in 2026.

Saipem, Alboran Hydrogen team up on H_2 plant construction

The companies signed an MOU for the joint development and construction of five plants for the production of green H_2 from electrolysis, three of which are slated for Puglia, Italy (Brindisi, Taranto and Foggia) and the other two for the Mediterranean basin (Albania and Morocco). The latter two plants will produce ammonia from green H_2.

ASIA-PACIFIC

Linde, Hyosung partner to develop H_2 infrastructure in Korea

Linde is partnering with Hyosung Corp. to build, own and operate extensive liquid H_2 infrastructure in South Korea. This H_2 network will support the country's decarbonization agenda to achieve net zero emissions by 2050.

On behalf of the JV, Linde will build and operate Asia's largest liquid H_2 facility. With a capacity of more than 30 tpd, the facility will process enough H_2 to fuel 100,000 cars and save up to 130,000 tpy of CO_2 tailpipe emissions. Based in Ulsan, the plants will use Linde's proprietary H_2 liquefaction technology, which is used to produce approximately half of the world's liquid H_2 at present. The first phase of the project is expected to start operations in 2023.

Under the partnership, Linde will sell and distribute the liquid H_2 produced at Ulsan to the growing mobility market in South Korea. To enable this, the JV will build, own and operate a nationwide network of H_2 refueling stations.

Air Liquide, Itochu to scale up Japan H_2 mobility

Air Liquide Japan and Itochu Corp. have signed an MOU to collaborate on the development of H_2 mobility markets in Japan. Air Liquide Japan and Itochu will initially focus on H_2 retail infrastructure in Japan, both for passenger vehicles and for new fleets of commercial vehicles.

The objective is to expand this retail infrastructure and develop a competitive H_2 supply for passenger and commercial end users, in collaboration with public authorities, allowing a rapid ramp-up of H_2 mobility in Japan. The two companies also will investigate global opportunities to scale up the H_2 supply chain in support of the Japanese government's H_2 roadmap.

HHIH partners with Saudi Aramco for blue H_2

South Korea's Hyundai Heavy Industries Holdings (HHIH) has made a deal with Saudi Arabia's state-run oil firm, Saudi Aramco, to cooperate on an H_2 project, with HHIH subsidiary Hyundai Oilbank importing LPG for blue H_2 production from Saudi Aramco.

In addition, CO_2 captured and stored during the production process will be provided to Saudi Aramco for the extraction of crude oil from spent oil fields. Hyundai Oilbank plans to sell blue H_2 as fuel for vehicles and thermal power plants or for use with desulfurization equipment, and is planning to establish 300 H_2 charging stations throughout South Korea by 2040. The company will also receive blue ammonia from Saudi Aramco.

Maire Tecnimont, Adani Enterprises to develop green H_2 in India

Through its subsidiaries NextChem, Stamicarbon and MET Development, Maire Tecnimont has signed an MOU with Adani Enterprises to produce chemicals, ammonia and H_2 from renewable feedstock. The partnership will utilize NextChem and Stamicarbon's technologies and MET Development's project development capabilities and expertise to industrialize green chemistry and circular economy sectors in India.

NORTH AMERICA

Evolugen, Gazifère plan large-scale H_2 injection project for Canada

Evolugen and Gazifère Inc. are planning one of Canada's largest green H_2 projects for injection into a natural gas distribution network in Québec. The companies plan to build and operate a 20-MW electrolyzer to produce H_2 in the Masson sector of Gatineau, adjacent to Evolugen's hydroelectric facilities, which will power the electrolyzer.

An estimated capacity of 425,000 GJ of green H_2 will be produced for injection into Gazifère's natural gas distribution network. The project is also anticipated to remove approximately 15,000 metric tpy of GHG emissions.

MMEX Resources plans blue H_2 project in Texas

MMEX Resources Corp. will establish an H_2 production project with carbon capture at its existing steam methane reforming site in Pecos County, Texas. Along with European partner Black Tree Energy Group, SCM and their U.S. unit, V Engineering & Consulting LLC, MMEX will develop and finance the H_2 project. MMEX is also studying additional H_2 project plant site locations in East Texas, the Houston ship channel area and the Corpus Christi/Rockport area.

Plug Power to operate two H_2 liquefaction plants in U.S.

Plug Power has placed an order for two 15-tpd H_2 liquefaction plants, in line with its strategy to build the first green H_2 generation network in the U.S. The H_2 liquefaction plants will utilize Chart's refrigeration technology, cold box design and associated rotating equipment.

Delivery is scheduled for Q2 2022. The liquefaction system will utilize gaseous H_2 from Plug Power's in-house electrolyzers and renewable electricity. The plants will be located in the Mid-Atlantic and Southeast regions, and are expected to be online before the end of 2022.

Southern Co. launches H_2 R&D initiative

The Southern Co. Gas subsidiary is launching a new R&D initiative, known as HyBlend, to address the technical barriers to blending H_2 in natural gas infrastructure and to study lifecycle emissions of H_2 blends.

The HyBlend project will encompass more than $15 MM in H_2 research. Research areas include lifecycle emissions of H_2 blends and techno-economic analyses of the costs and opportunities of H_2 production. The project will leverage the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office's Hydrogen Materials Compatibility Consortium.

Nikola unveils North American FCEV program

Following the launch of North American production of the Tre battery-electric vehicle (BEV), Nikola plans to introduce an H_2 FCEV variant of the Nikola Tre Cabover, and the long-range Nikola Two FCEV Sleeper targeting efficiency for ranges of 300 mi–900 mi in the North American market.

The Nikola portfolio includes trucks for metro/regional (Tre BEV Cabover for trips up to 300 mi), regional (Tre FCEV Cabover for up to 500 mi and for fast fueling) and long-haul (Two FCEV Sleeper for up to 900 mi).

The first Tre FCEV prototype builds are scheduled to begin in Arizona, U.S. and Ulm, Germany in Q2 2021, with testing and validation of the vehicles continuing into 2022 and production planned for H_2 2023.

SOUTH AMERICA

Aker Clean Hydrogen, Mainstream partner for green H_2 in Chile

The two companies will collaborate on a complete and commercially viable green value chain in Chile, using renewable power from Mainstream's 1.3-GW Andes Renovables wind and solar generation platform, which is slated for startup in late 2021. Green H_2 and green ammonia produced using the renewable power will be used by several industrial consumers locally in South America and also exported to other markets.

Aker Clean Hydrogen has a portfolio of nine clean H_2 projects and prospects with a total net capacity of 1.3 GW under development, and additional pipeline and other opportunities of 4.7 GW. The company aims to reach a net installed capacity of 5 GW by 2030.

Enegix to build $5.4-B green H_2 facility in Brazil

Enegix Energy aims to build the largest green H_2 plant in Ceará, Brazil, after signing an MOU with the state government. The green H_2 plant is anticipated to produce more than 600 MMkgy of green H_2 from 3.4 GW of combined baseload wind and solar power through a partnership with Enerwind. The project is expected to take 3 yr–4 yr to build.

MIDDLE EAST

Mubadala, Snam to explore H_2 in UAE

Mubadala Investment Co. and Snam have signed an MOU to collaborate on joint investment and development initiatives for H_2. As part of the agreement, the two companies will carry out a number of assessment activities, including technical and economic feasibility studies to explore potential projects and solutions to foster and promote H_2 development in the UAE and elsewhere.

SOUTH AMERICA

Fortescue, EIG explore green H_2 development in Brazil

EIG and Fortescue Future Industries have signed an MOU to jointly conduct feasibility studies for the installation of a green H_2 plant at the Port of Açu, South America's largest privately owned deepwater port-industrial complex.

The proposed green H_2 plant would have 300 MW of capacity with the potential to produce 250,000 metric t of green ammonia. The availability of green H_2 and renewable power is expected to drive further sustainable industrialization at the port, including production of green steel, fertilizers, chemicals, fuels and other sustainably manufactured industrial products.

REGIONAL REPORT: ASIA-PACIFIC

Japan, Australia forge a path for Asia-Pacific H_2 development

A. BLUME, Editor-in-Chief

Asia-Pacific is forecast to be the fastest-growing region in hydrogen to 2025, as governments continue to adopt green technologies to meet national targets for CO_2 emissions reduction. Estimated potential demand for imported H_2 in China, Japan, South Korea and Singapore could reach $9.5 B by 2030.[1] China, in particular, is in need of reliable, clean backup power as the growth of renewable energy has made its electric grid increasingly unstable.

Australia and Japan are two of Asia-Pacific's leaders in H_2 network development, and have established their own clean energy and carbon emissions reduction strategies. They have also signed a joint statement of cooperation with each other for H_2 and fuel cell development.

Fitch Ratings estimated that Asia's electrolyzer capacity could surpass 10 GW by 2030, although green H_2 projects remain a wild card that could accelerate this capacity dramatically toward the end of the decade. The development of green H_2 capacity is closely linked to the abundance of affordable renewable electricity and the need for backup power. Many estimates expect that the cost of electrolyzers could halve and allow green H_2 to reach market parity with gray (fossil-based) H_2 by 2030. Asia-Pacific remains the fastest-growing region for both energy demand and renewable power growth over the coming decades.

National initiatives and projects across Asia-Pacific to produce and incorporate H_2 into the energy mix are discussed in the following sections.

OPENING PHOTO: Kawasaki Heavy Industries' *Suiso Frontier* liquefied H_2 carrier—the first of its kind—at the Kobe shipyard in late 2020. Photo: Wikimedia Commons.

Japan. In 2017, Japan became the first regional government to adopt a national H_2 framework. This framework was followed by the "Strategic roadmap for hydrogen and fuel cells" in March 2019, which envisages significant consumption of H_2 in Japan in the near future.

One complication to boosting H_2 consumption is the high cost. Japan's Ministry of Economy, Trade and Industry (METI) estimates that the cost of H_2 must decrease to ¥20/m^3—almost on par with the cost of LNG—to be commercially viable. To reduce H_2 costs, Japan has raised its consumption goal for H_2 to 5 MMt–10 MMt and set forth initiatives for increased H_2-fueled backup power generation and greater adoption of fuel cell electric vehicles (FCEVs). The government hopes to bring down the cost of blue H_2 (with carbon capture) to ¥30/m^3 by 2030.

Japan has been investing heavily in fuel cell technologies over the past 12 yr, after it began commercially offering fuel cell-powered, micro-scale combined-heat-and-power (CHP) systems. By 2030, Japan aims to significantly increase the amount of power it generates using H_2, with plans to burn approximately 10 MMtpy by that year—roughly equivalent to the power produced by 30 nuclear reactors.

In addition to more wind and solar power, the increase in H_2-driven power generation will help Japan reach carbon emissions neutrality by 2050—a target announced by Prime Minister Yoshihide Suga in September 2020. To this end, the Japan Hydrogen Association (JH2A), formed in late 2020, is promoting H_2 in a number of areas for decarbonization.

H_2 projects. A major project, led by Chiyoda and Nippon Yusen, launched a demonstration H_2 global supply chain in 2020. Chiyoda's technology adds toluene to H_2, creating a more stable substance for transportation and storage. The toluene must be removed before the H_2 can be used in fuel cells, but the stabilized H_2 can be transported with a normal ship used to ship chemical products. Chiyoda shipped H_2—produced in Brunei from waste gas—in a tanker in three round trips between Brunei and Japan, suppling approximately 110 t of H_2. Read the Chiyoda-contributed article on this topic in the Q1 2021 issue of *H2Tech*.[2]

Toshiba offers technology to convert electricity to H_2, which can be stored for use during times of unstable power supply from renewable energy. Toshiba is also a player in one of the world's largest operating green H_2 plants, the 10-MW Fukushima Hydrogen Energy Research Field (FH2R) (COVER PHOTO). The FH2H project opened in March 2020 in Fukushima, Japan. The 100 kg/hr of H_2 produced at the complex via solar-powered electrolysis will be able to fill 560 fuel cell vehicles per day, and will be used in buses and other vehicles (FIG. 1).

Among marine applications for H_2, Japan's Kawasaki Heavy Industries has developed the world's first vessel to ferry liquefied H_2, the *Suiso Frontier* (OPENING PHOTO). The company also plans to commercialize large H_2 ships by 2030. The *Suiso Frontier* is slated to begin H_2 shipments from Australia to Japan in 2021. Also, Iwatani and Kansai Electric Power plan to commercialize H_2-powered fuel cell vessels by 2025.

Several test projects between Japan and potential suppliers in the Middle East also have been established. These projects include the world's first shipment of blue ammonia from Saudi Arabia to Japan in September 2020 and the active role being taken by Japan in Oman's new H_2 roadmap.

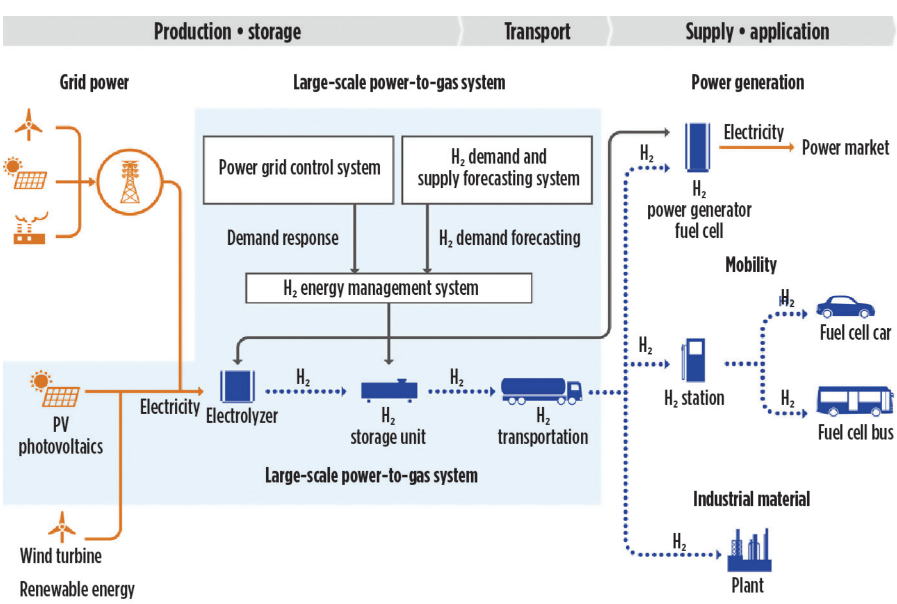


FIG. 1. Overview of the FH2R system. Image: Toshiba.

Australia. The "Land Down Under" aims to become a major H_2 producer by 2030 under its "National hydrogen strategy," released in November 2019. One report calculated that global demand for H_2 exported from Australia could exceed 3 MMtpy by 2040, which could contribute up to A$10 B/yr to the country's economy.[3] Initial key customers are expected to be Japan and South Korea.

On the offense with H_2. Coal and LNG make up 25% of Australia's total exports at present, and resource-scarce Japan is a major importer of Australian energy. However, Japan's late-2020 announcement of its plan to reach carbon net neutrality by 2050 served as a wakeup call to Australia, which is now racing to further decarbonize and expand its clean energy portfolio.

What began as a defensive maneuver for Australian energy producers and suppliers has turned into a strategic offensive. The country's natural gas pipeline owners are looking to future-proof their A$75 B of assets by conducting tests to blend H_2 with natural gas and produce "greener" methane. Some Australian states are pushing for a 10% H_2 blend in gas pipelines by 2030, which can be safely accommodated without modification to infrastructure or appliances.

Blending H_2 into the natural gas network will allow for a scale-up of H_2 production, requiring the initial installation of smaller (1-GW-capacity) electrolyzers before more H_2 is needed. As the H_2 network expands, so will the need for larger, more expensive electrolyzers for green H_2 production. Residential trials with a 5% H_2 blend are already underway in Adelaide at the A$11.4-MM Hydrogen Park

South Australia (HyP SA) demonstration project.

Furthermore, the Australian Renewable Energy Agency (ARENA), together with the Australian government, is providing A$1.28 MM in funding for the establishment of the Australian Hydrogen Center. The project will study blending H_2 into existing natural gas pipelines in South Australia and Victoria.

H_2 projects. The **Western Australian** government has recently accelerated its "Renewable hydrogen strategy" by a decade (from 2040 to 2030) and will invest A$22 MM toward the development of the state's H_2 industry. Among major H_2 initiatives under development, a A$51-B project to mass-produce H_2 from wind and solar power is underway. The Asian Renewable Energy Hub aims to meet Australia's 2030 H_2 price point of A$2/kg ($1.50/kg); production costs for green H_2 are around A$3.18/kg–A$3.80/kg, at present. The project will produce 1.75 MMtpy of H_2 from 26 GW of renewable power for conversion into ammonia for domestic and international markets. Construction is expected to start in 2026, with first shipments anticipated in 2028.

Also in Western Australia, the Arrowsmith H_2 project is a proposed green H_2 production plant near Dongara, 320 km north of Perth. The A$300-MM project, led by Infinite Blue Energy, is expected to start up in mid-2022 and produce 25 metric tpd of green H_2 from water, wind and solar energies.

The Hazer Group will build a 100-metric-tpy facility to convert biogas from sewage treatment into fuel cell-grade H_2. The project commenced in March 2020 and is planned to run through the middle of the decade. Also, Hydrogen Renewables Australia Ltd. is proposing a large-scale (up to 5,000 MW) combined wind and solar farm in Murchison to produce low-cost green H_2 for export to Asia.

Furthermore, Australian utility ATCO is working with mining firm Fortescue to deploy a pilot H_2 vehicle refueling infrastructure in Western Australia. Under the agreement, ATCO and Fortescue will construct and operate the refueling facility at ATCO's existing facility in Jandakot.

The **South Australian** government has invested more than A$17 MM in grants and A$25 MM in loans for four green H_2 projects. These projects include Neoen's plans to construct a A$600-MM renewable H_2 production facility to support its solar and wind generation facilities at the Crystal Brook Energy Park in South Australia. The proposed, 50-MW H_2 super-hub would be the largest co-located wind, solar, battery and H_2 production facility in the world, producing about 7,000 metric tpy of H_2.

With a mix of H_2 suppliers and consumers and a quickly expanding renewable energy base, Asia-Pacific will play a leading role in global market dynamics for low-carbon H_2.

Another project is The Hydrogen Utility's Eyre Peninsula Gateway Project, which will develop a facility integrating more than 75 MW in water electrolysis to produce renewable H_2 and renewable ammonia on the Eyre Peninsula. With a total production capacity of up to 40,000 tpy of green ammonia, the facility will supply the domestic market and support trial export shipments of green H_2 and green ammonia to Japan and other North Asian countries.

The **Victorian** Government has introduced the Victoria Hydrogen Investment Program, which has invested A$2 MM to boost the development of clean H_2 technologies in Victoria—specifically, Deakin's project for the creation of an H_2 supply chain project in Warrnambool.

Elsewhere in Victoria, a consortium of Japan's Kawasaki Heavy Industries, J-Power, Iwatani, Marubeni, Sumitomo and Australian utility AGL announced the commencement of operations at both Victorian sites of its integrated supply chain. The A$500-MM Hydrogen Energy Supply Chain (HESC) project is developing a complete H_2 supply chain by producing H_2 via the gasification of Latrobe Valley lignite coal, transporting it to the Port of Hastings for liquefaction, and then shipping it to Japan (FIG. 2). H_2 production commenced in February 2021. At commercial scale, the project could produce 225,000 tpy of low-carbon blue H_2, according to the partners.

In **Queensland,** Origin Energy is working with Japan's Kawasaki Heavy Industries on a green liquid H_2 export project in Townsville. Furthermore, APA Group is building a power-to-gas demonstration plant at its Wallumbilla gas hub near Roma to create methane using solar-generated electricity, water and CO_2 from the atmosphere. The A$2.26-MM project will produce approximately 620 kg/yr of H_2 for conversion into 74 GJ of methane, which can be injected into APA

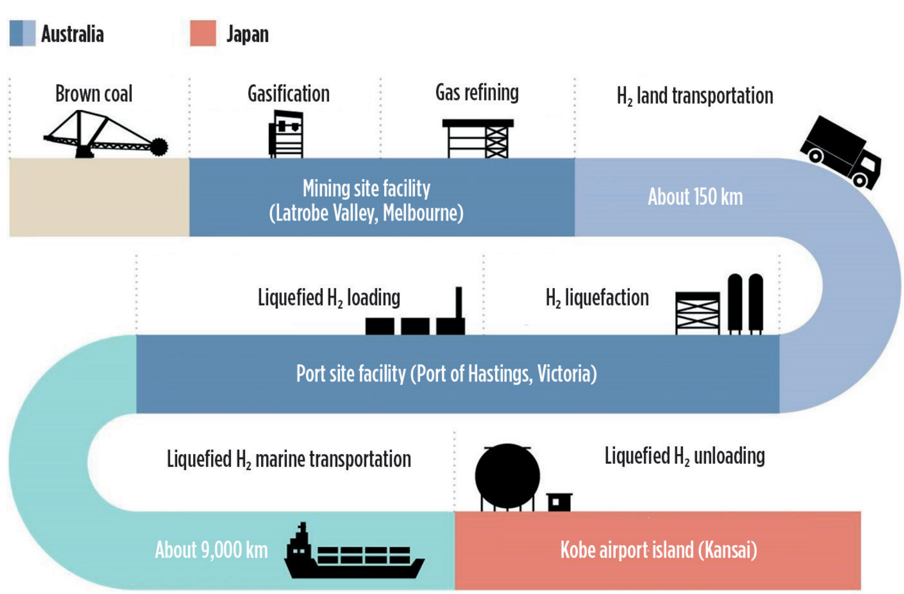


FIG. 2. Details of the Australia–Japan Hydrogen Energy Supply Chain (HESC) project. Image: HySTRA.

Group's natural gas pipelines across the East Coast Gas Grid.

BOC Ltd., together with partners ITM Power, Queensland University of Technology and Hyundai Motor Co. Australia, are installing a 220-kW electrolyzer and a 100-kW solar array to produce renewable H_2 through electrolysis at BOC's Bulwer Island, Queensland site. The electrolyzer will have capacity to produce up to 2,400 kg/month of renewable H_2 to power FCEVs and supply BOC's industrial customers. Since the closure of the BP refinery at Bulwer Island, BOC has transported H_2 from its Altona facility in Melbourne, Victoria to Bulwer Island in high-pressure tube trailers, resulting in 90,000 kg of CO_2 emissions. BOC sees the opportunity to demonstrate ultra-high-pressure refueling of H_2 FCEVs, powered by renewable H_2 produced at Bulwer Island.

Eco Energy World (EEW) plans to produce green H_2 using power from a planned, 300-MW solar farm in Raglan near the Port of Gladstone, Queensland. The plant will produce 33,000 tpy of green H_2 and represent one of the world's largest green H_2 and solar photovoltaic developments. Construction of the \$500-MM project is expected to start in Q3 2022.

The **New South Wales** government has offered A\$15 MM in grants for regional community energy, including New South Wales' first H_2 energy storage system at Manilla.

A number of additional H_2 and renewable energy projects are ongoing in Australia, with many in the feasibility, proposal and planning stages.

China. China is the world's largest H_2 producer, with more than 20 metric MMtpy of gray H_2 output, or approximately one-third of the world's total. This puts China's H_2 supply at about three times that of the entire H_2 supply of Europe (7 metric MMtpy).[4]

China's government is sponsoring low-carbon H_2 research and development, and the Beijing city government has announced plans to have more than 1,000 fuel cell buses in operation for the 2022 Winter Olympics. Two H_2 refueling stations have been opened in Shanghai since 2019, and the government has declared a target of 1,000 stations by 2030, along with 1 MM FCEVs in use on China's roads.

Furthermore, Sinopec is studying the development of green H_2 technology in China, as the nation seeks to reach net zero carbon emissions by 2060.

South Korea. The country unveiled its H_2 roadmap in 2019, with a vision to sharply increase the production of H_2-powered vehicles and electricity generation by H_2. In 2020, the Korean National Assembly passed the Hydrogen Economy Promotion and Hydrogen Safety Management Law, laying the legal foundations for the government's H_2 commitment and implementing safety standards for H_2 facilities.

Meanwhile, Korea Gas Corp. plans to boost H_2 production by building 25 production bases nationwide, along with constructing new supply chains and distribution channels. It also plans to invest in liquefied H_2.

Malaysia. National energy giant Petronas announced a partnership with Japanese LNG importer JERA in February 2021 to collaborate on a wide range of low-carbon energy initiatives covering H_2, ammonia and LNG. Petronas established an H_2 business unit in November 2020 and is already producing blue H_2 at its refineries.

The company is also foraying into green H_2, as part of its effort to achieve carbon net neutrality by 2050. In late 2020, Petronas announced that it would partner with SEDC Energy, a subsidiary of state-owned utility Sarawak Economic Development Corp., for a large-scale, hydropower-driven H_2 production facility.

FCEVs and refueling networks. Worldwide, 584 H_2 refueling stations were deployed as of the end of 2020, with half of these located in Asia-Pacific and one-third located in Europe. Within the Asia-Pacific region, **Japan** leads in H_2 refueling station installations with around 150, although **China** has already deployed more than 100 stations in a short period of time.

At present, Japan's H_2-powered vehicle fleet numbers fewer than 4,000; many of these vehicles are owned by the government. Japan aims to have 200,000 H_2 FCEVs and 320 H_2 refueling stations in use by 2025. To this end, Japanese automaker Toyota introduced the Mirai—meaning "future" in Japanese—in 2014 as the world's first commercially produced, H_2-fueled vehicle. Recent improvements to functionality, such as the 30% increase in Mirai driving distance offered on Toyota's newest model, are anticipated to enhance the attractiveness of H_2-fueled transportation.

Meanwhile, **South Korea** already hosts enough refueling stations to enable a cross-country drive via FCEV. The country's 2020 economic strategy includes the provision of 200,000 H_2 vehicles and 450 FCEV charging facilities by 2025. Korea's Hyundai Motor Co. began production of an H_2-electric hybrid car in 2013 and launched the Nexo FCEV in 2018.

It is predicted that, by 2035, H_2 stations will be commonplace throughout most of China, Japan and South Korea—in addition to Western Europe and the U.S. Also, **Thailand's** government is encouraging electric transport, which opens up a potential market for H_2 fuel cells.

Takeaway. The Asia-Pacific region is expected to dominate the global H_2 market between 2020 and 2025, adopting green technologies to meet government targets for reducing GHG emissions. With a mix of H_2 supplier and consumer countries and a quickly expanding renewable energy base, Asia-Pacific will play a leading role in global market dynamics for low-carbon H_2.

Japan and Australia are the leaders in H_2 projects and synergies, although China is working at a rapid pace to expand its H_2 infrastructure. H_2 use in South Korea, Malaysia and other countries will increase alongside the growth of regional and global supply networks and technology installations to expand the industrial and commercial use of H_2. These ongoing efforts will make Asia-Pacific a region to watch for H_2 development through 2030 and beyond.

LITERATURE CITED

1. Purtill, J., "What is green hydrogen, how is it made and will it be the fuel of the future?" ABC Science News, January 22, 2021, Online: https://www.abc.net.au/news/science/2021-01-23/green-hydrogen-renewable-energy-climate-emissions-explainer/13081872
2. Schneider, R. V., D. Kurosaki and M. Oki, "Advances in chemical carriers for hydrogen," *H2Tech,* Q1 2021.
3. ACIL Allen Consulting for Australian Renewable Energy Agency, "Opportunities for Australia from hydrogen exports," Melbourne, Australia, August 2018, Online: https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf
4. Asia-Pacific Hydrogen Association, "China ponders subsidies, cheaper technology for its hydrogen roadmap," S&P Global Platts, May 13, 2020, Online: https://apac-hydrogen.org/china-ponders-subsidies-cheaper-technology-for-its-hydrogen-roadmap

MARINE APPLICATIONS

Hydrogen poised for growth as cargo and marine fuel

S. MAMALIS, American Bureau of Shipping (ABS), Houston, Texas

Measures in CO_2 reductions are emerging across the globe. With the strong correlation between transport activity and GDP growth, decoupling transport emissions from GDP growth is one of the largest challenges facing industry today.

Good progress is being made, and a number of evolving technology and energy-efficiency measures are available to decrease air pollution and greenhouse gas emissions. However, to succeed in cutting total greenhouse gas emissions, energy-efficiency measures alone are not enough. The need exists for low-emitting alternative fuels in the decarbonizing journey.

One possible "near-term" solution is H_2—a zero-carbon fuel that is being considered for use in marine applications. The other zero-carbon fuel is ammonia, and the production pathway of the two are interlinked. H_2 can be produced from many different sources, utilizing conventional or renewable energy, which determines the cost of the fuel to the end user as well as its lifecycle carbon footprint.

The potential of H_2 to offer zero-emissions power generation and propulsion has made it attractive to various industry sectors and governments worldwide. Countries such as Japan and South Korea have published H_2 economy roadmaps showcasing ambitious goals. Japan aims to commercialize H_2 power generation along with international H_2 supply chains, as well as reduce the unit cost of H_2 power generation to \$0.16/kWh by 2030. South Korea is projected to develop an H_2 market of more than \$24 B by 2030 in an effort to deploy 15 GW of utility-scale fuel cells and 2.1 GW of commercial and residential fuel cells by 2040. The EU Hydrogen Strategy estimates up to \$570 B of investments, with Germany, Spain and France leading the way.

Similar initiatives are expected to be announced by other countries and governments in the following years. The wide adoption of H_2 as a fuel for stationary power generation, automotive, marine and aviation applications will create an opportunity for the marine sector to carry H_2 as cargo and support the global supply chain from the production to the consumption sites. However, this opportunity comes with some challenges, primarily associated with the design and construction of liquefied H_2 carriers (LHC), the development of port site facilities for H_2 liquefaction and loading, as well as facilities for H_2 unloading and storage at the destination terminals.

In late 2019, Kawasaki Heavy Industries introduced the first liquefied H_2 carrier (**FIG. 1**), capable of carrying 1,250 m^3 of H_2 over a range of 4,860 nautical miles from Australia to Japan. The *Suiso Frontier* uses a vacuum-insulated, double-shell cargo tank capable of storing H_2 at –253°C and a diesel-electric propulsion system. Kawasaki also partnered with the Port of Hastings in Victoria, Australia to develop the required H_2 liquefaction and loading facilities, and developed the unloading terminal in Kobe, Japan.

The experience and technical know-how gained from LNG carriers will enable the shipping industry to build and operate liquefied H_2 carriers at an accelerated pace. However, the design and operation of liquefied H_2 carriers will pose more stringent requirements to the vessel due to the high diffusivity of the fuel and the lower temperatures required for cryogenic storage. The natural boiloff gas from the cargo will enable the vessels to use H_2 in a fully electric propulsion system based on fuel cells. Such a configuration can eliminate tank-to-wake carbon emissions,

FIG. 1. Kawasaki Heavy Industries' *Suiso Frontier* liquefied H_2 carrier at the official naming and launch at Kobe Works. Photo: Kawasaki.

increase the efficiency of the vessel, and minimize noise and vibration to improve the habitability of the vessel for the crew. Additional benefits can be realized by zero-emissions cold ironing, as well as integration of all the auxiliary systems of the vessel for purely electric operation.

For vessels other than liquefied H_2 carriers, H_2 storage onboard will require 4.6 times larger volume compared to very-low-sulfur fuel oil, which poses design and operational constraints. The operating profile of such vessels must be tailored to trade routes that offer access to H_2 bunkering.

The International Council on Clean Transportation (ICCT) recently completed a study on green H_2 bunkering infrastructure for trans-Pacific container shipping that offers zero-carbon lifecycle emissions. It investigated the potential to develop liquefied H_2 storage and bunkering infrastructure at multiple locations from the west coast of the U.S. and Canada and the Aleutian Islands, all the way to Japan, South Korea and China. By analyzing 2015 operations, they found that the associated ports would need to supply 730,000 tpy of H_2 to fuel all the container ships trading in this corridor. This number corresponds to about 1% of the H_2 used in the industrial sector worldwide in 2019.

The ICCT study was based on using 2,500-m^3 cryogenic spherical tanks for onsite H_2 storage. Based on the bunkering needs of different ports along the Pacific Rim, the study estimated the required amount of tanks to range from three in east South Korea to 39 in San Pedro Bay, corresponding to less than 1% of the area used in the port in every case.

Such studies prove the technical feasibility of H_2 as cargo and marine fuel and pave the way to strategic planning for developing the required infrastructure across the globe. While the cost of bunkering facilities is expected to be higher than that of LNG facilities, primarily because of the higher cryogenic storage requirement of liquid H_2 and the material required for tanks, pipes and seals, the main cost components are the storage and bunker vessels, which must be scaled based on the number of ships serviced. Onsite availability of H_2 would be needed for small ports, given the lower flows and high cost of dedicated H_2 pipelines. However, ship and infrastructure costs are a relatively small fraction of total shipping costs over a typical 15 yr–20 yr life span, with the fuel cost being the primary factor.

The economic feasibility of H_2 as fuel is supported by its wide applicability across different sectors, such as green H_2 production from renewable energy and subsequent production of green ammonia, methanol or other hydrocarbon fuels. The direct use of H_2 for distributed generation, combined heat and power, aviation, marine and automotive applications, all the way to green steel production, will also lead to economies of scale that will make green H_2 economically attractive.

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EXECUTIVE VIEWPOINT

Maire Tecnimont CEO touts focus on circular hydrogen

PIERROBERTO FOLGIERO, CEO, Maire Tecnimont Group and Managing Director, NextChem

PIERROBERTO FOLGIERO is the CEO of Maire Tecnimont Group and the Managing Director of NextChem. He joined Maire Tecnimont Group in September 2010 as CFO of KT SpA, the Group's licensor and process engineering contractor in oil and gas refining, and took the position of Managing Director of the company in June 2011. In May 2012, he was appointed Managing Director of Tecnimont SpA, the Group's large-scale EPC contractor in hydrocarbon processing. In May 2012, he was appointed COO of Maire Tecnimont SpA, and became CEO of the entire Group in May 2013.

From April 2019, Mr. Folgiero also assumed the position of Managing Director of NextChem, a new company of the Group that operates in the field of green chemistry and in energy transition supporting technologies. He is also Chairman of the Supervisory Board of Stamicarbon, the licensing and IP excellency center of the Group.

Mr. Folgiero started his career at Agip Petroli before moving to Ernst & Young as an Experienced Assistant and later to PricewaterhouseCoopers as Corporate Finance Manager. In 2000, he joined WIND Telecomunicazioni SpA, becoming Corporate Development Director in 2006. In June 2008, he joined Tirrenia di Navigazione SpA as Chief Financial Officer and General Manager, where he spearheaded the shipping company's restructuring and privatization process.

He graduated in economics studies from Luiss Guido Carli University in Rome in 1995, where he is now a member of the university's advisory board, and he is a chartered accountant in Italy.

H2Tech recently spoke with Pierroberto Folgiero, CEO of Maire Tecnimont Group and Managing Director of NextChem, Maire Tecnimont's company for green chemistry and energy transition technologies, about the Group's H_2 development projects and H_2 outlook.

H2T. NextChem is designing and building the pilot unit for the EU's PROMETEO project as part of its Horizon 2020 initiative. What is special about this project?

PF. The plant is based on solid oxide electrolysis (SOE), a highly efficient technology that converts heat and power into H_2 from water, powered by renewable energies. The challenge is to optimize the coupling of the SOE with two intermittent renewable energies: non-programmable renewable electricity (wind or photovoltaic) and high-temperature solar heat from concentrating solar systems with thermal energy storage to supply solar heat when power is made available.

H2T. What learnings do the PROMETEO Consortium partners hope to achieve from this project, and how will the results be applied to future projects?

PF. The ambition of the consortium is to make significant advances toward integrated SOE technology, which maximizes H_2 production efficiency and minimizes the impact of renewable energies intermittency by incorporating the solar thermal energy storage. To this end, the PROMETEO project addresses key innovations involving development and validation at semi-industrial scale. The project will also develop a portfolio of tools for optimization, system performance and dynamic performance analysis that can be applied to future projects.

H2T. NextChem recently signed an MOU with Enel Green Power for H_2 production for a biorefinery in the U.S. via electrolysis, using solar power. What is NextChem's role in this venture?

PF. Maire Tecnimont, through NextChem and Enel Green Power and through its North American renewables subsidiary, Enel Green Power North America Inc., has signed an MOU to support the production of green H_2 via electrolysis in the U.S. Enel, with a strong track record of project commercialization and a large renewable operations footprint in the U.S., will leverage NextChem's H_2 technology and engineering expertise to grow its green H_2 business in the U.S.

The project, which is expected to be operational in 2023, will convert renewable energy from one of Enel Green Power North America's solar plants in the U.S. into green H_2 to be supplied to a biorefinery. Under the agreement, NextChem will act as technology and engineering partner and full turnkey EPC contractor, providing Enel Green Power with the necessary technical assistance in relation to the development and implementation of the project.

We are very proud to be Enel's partner of choice in this industrial initiative, which enhances our Group's expertise in the H_2 chemistry applied for the production of green H_2 from solar energy and which represents a relevant step in the development of our green H_2 initiatives. The U.S. market is really interesting for us, and we are looking at it with great attention.

The agreement represents the first application of a framework cooperation agreement between Enel and NextChem to evaluate the implementation of joint projects, including the testing of advanced technologies to increase efficiency in the production of green H_2 using renewables.

H2T. What obstacles must H_2 overcome to become a significant contributor to the world's energy supply by 2050?

PF. The development of an H_2-based system requires investments, a strong political will and a synergic and cross-sectoral approach. Radical changes to industrial plant technologies and transport and distribution networks can only be supranational and interconnected.

A comprehensive view is needed to develop an H_2-based system, and synergies must be created among sectors as different as energy, manufacturing and transportation. Synergies must be enabled among these sectors to make them "talk" each other, standardize their "languages," and share knowledge, data and information.

H2T. Broadly speaking, in what sectors do you see H_2 having the greatest chance for success? How can business models be transformed to include more H_2 in the energy mix?

PF. Power generation, transportation, shipping and manufacturing are crucial sectors for H_2 development. H_2 is a building block of chemistry, has a strategic role as a fuel both for industrial processes and mobility, and it also has a key role in the storage of electricity from renewable energy.

It is estimated that 23% of energy in Europe will come from H_2 in 2025, but what is the best mix to reach this goal? Today, natural gas is the source of most of the H_2 produced, using steam methane reforming (SMR) to produce gray H_2. The production process, which uses natural gas or coal as feedstock, is a strong contributor to CO_2 emissions.

NextChem is studying and developing technologies for low-carbon H_2 that may help the transition to a full green H_2 economy. NextChem has also developed a technology for circular H_2 produced from waste by recovering its carbon and H_2 content through chemical conversion.

Another method of H_2 production is blue H_2, produced with SMR from natural gas or coal but with CO_2 emissions captured and stored. A third method is the production of green H_2 via electrolysis, using power from off-grid renewable energy like wind and solar.

Green H_2 is the lowest-carbon-intensive option; nonetheless, there are several challenges related to its production. While the technology is well known, the costs associated with it are high at present. The cost of conventional (gray) H_2 is in the range of \$1/kg–\$3.5/kg (according to the raw materials used and whether or not carbon capture and storage is applied), while green H_2 shows higher production costs in the range of \$2/kg–\$7/kg, depending on renewable energy availability and pricing.

In this transition phase, before green H_2 reaches maturity, the options of Super Blue H_2 and circular H_2 could play an important role in the H_2 mix (**FIG. 1**). NextChem has developed technology solutions for these types of H_2, as we strongly believe in their potential role in the energy transition.

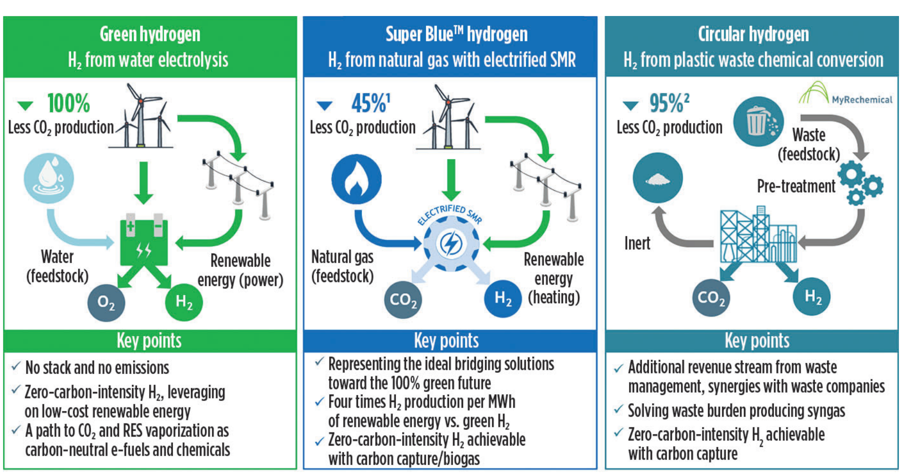

FIG. 1. Pathways for low-carbon hydrogen production, including Maire Tecnimont Group and NextChem's Super Blue hydrogen and circular hydrogen technologies.

H2T. What are Maire Tecnimont and NextChem's key plans for the H_2 market over the next decade?

PF. In addition to the blue and green H_2 solutions in our portfolio, NextChem is studying and developing innovative technologies for other types of low-carbon H_2 that may help the transition toward a full green H_2 economy.

Our Super Blue H_2 technology takes blue H_2 a step further by introducing the use of renewable energy. This approach allows a reduction of CO_2 emissions production by 50% and facilitates the total recovery of CO_2.

NextChem has also developed a technology for circular H_2 produced from waste by recovering its carbon and H_2 content through chemical conversion. Circular H_2 is the fourth type of H_2 available on an industrial scale after gray H_2, blue H_2 and green H_2. The synthetic gas (syngas) produced by waste gasification with pure O_2 at high temperature is a mixture of H_2 and CO. H_2 can be separated by the main stream up to high purity for industrial, mobility or residential applications, while CO can be used for chemical synthesis or converted to high-purity H_2 by reacting with steam.

Circular H_2, when used instead of gray H_2, allows a strong reduction of carbon footprint. The production cost is competitive compared to traditional H_2 from fossil sources, thanks to the reduced cost of waste disposal. Our technology is ready and validated. Plants for circular H_2 production can be placed in traditional industrial sites, such as refineries, serving as a functional decarbonization solution that offers a range of benefits, both from an environmental and a socio-economic perspective.

EXECUTIVE VIEWPOINT

Accelerating the future of green hydrogen

GORDON MUIR, President, Industrial Automation, Emerson Automation Solutions

GORDON MUIR is President of Industrial Automation at Emerson Automation Solutions. He has been following the hydrogen industry for more than 15 yr, with a special interest in green hydrogen. Gordon earned his MBA degree from the University of Minnesota and his BS degree in electrical and electronic engineering from the University of Strathclyde in Glasgow, Scotland.

The push for clean energy continues to drive interest in hydrogen-powered vehicles and power systems. The demand for green H_2 is greater than ever before, and many consider it to be one of the most viable near-future sources of energy. With this promising outlook ahead, the green H_2 industry is a pretty exciting place to be. With the right solutions and processes in place across the supply chain, we can bring the more sustainable future of green H_2 closer to reality, right now.

Creating a zero-emissions future. What makes green H_2 so attractive as a renewable source of energy is that it can provide sufficient, reliable, universal power with zero emissions. Countries around the world have developed policies, programs and projects to accelerate green H_2 production and use. Many governments have developed H_2 roadmaps and are setting ambitious targets. With eyes on the outcome, attention on green H_2 is only growing.

Since most of the infrastructure and processes required to support the transition to green H_2 still need to be built, scale-up remains a challenge. The good news is that technology solutions and digital transformation that have already been proven in the greater H_2 industry can help solve many of the challenges that companies across the value chain are facing now.

Hydrogen production. The process of producing H_2 using water and electricity is called electrolysis. Electricity breaks down water into its base elements, H_2 and O_2, in a unit called an electrolyzer. These electrolyzers can range from small devices to large-scale, central production facilities. For example, skid electrolyzers can power a single factory or entire communities. By combining electrolytic cells and stacks, green H_2 production can be scaled according to the needs of the application.

However, within the great advantages of scalable clean energy lie a few challenges. Research and development efforts are being made to increase electrolyzer system efficiency overall, as well as electrolyzer operating life, power density and stack size. These improvements will reduce material costs and lead to more flexible systems that are adapted to intermittent and fluctuating power supplies.

Due to the great scalability of electrolyzers, manufacturers must consider how they will access the components necessary for the full range of electrolyzer sizes. The nature of H_2 adds even more complexity. It is the smallest and the lightest element and, if mishandled, the consequences can be disastrous. Electrolyzer components must be reliable and built for hazardous environments to keep people and property safe.

Working with one technology supplier that has an extensive portfolio specifically designed for H_2 applications can simplify the supply chain, saving companies time and money as they scale their production. This frees equipment manufacturers and producers to focus on developing and delivering their products.

It is especially important to work with an expert supplier equipped with a wide range of measurement, control and electrical equipment specifically designed to improve reliability and safety in the hazardous areas of electrolyzers (FIG. 1). In addition to valves, valve systems, flowmeters, regulators and pressure transmitters, they should also have smart technologies, such as scalable process control and safety solutions that can reduce operational complexity, decrease risk and improve the performance of green H_2 facilities, from electrolyzers to balance of plant assets, while providing sitewide safety system capabilities. An integrated control and safety system (ICSS) is also a critical tool to ensure optimized start/stop sequencing with embedded sequence diagnostics.

Conversion, storage and transport. Before H_2 can be used for power, it must be converted, stored or transported. With pressures of up to 15,000 psi in the value chain, H_2 must be effectively, efficiently and safely controlled. No inboard or outboard leaks can occur due to integrity issues with static or dynamic seals. Even some metals can be negatively affected by prolonged exposure to H_2, a process called H_2 embrittlement. Risk assessments and strict regulations must also be met.

Working with H_2 requires serious, dependable control to ensure that systems operate safely. Companies need to know that they do not have loss across their systems, and they need to know how much H_2 is passing through transmission/transfer points. Integrating components that reliably monitor and measure H_2 into systems is essential.

Every system includes certain final control elements (FCE), such as shutoff and metering valves, high-pressure regulators, pneumatic actuators and solenoid valves. Reliable, high-quality control and safety circuits provide the precision necessary to maintain appropriate pressure and flowrates and preserve H_2 purity, and can be monitored remotely. Sensors should be integrated to monitor pressure, temperature and flowrates. If smart equipment is used, data can be collected to improve productivity and ensure high operational yields.

It is also important to have a supplier with a complete portfolio. What is even more important, however, is working with partners with extensive H_2 experience and expertise that are familiar with the regulations and certifications. They understand the plantwide ecosystem and have the safety and controls equipment needed to monitor, measure and control H_2 effectively and efficiently. They should also have the flexibility to address a vast range of designs and applications.

FIG. 1. It is beneficial to work with a trusted central partner across the entire H_2 fuel value chain.

Mobility. A key element of the transition to H_2-powered vehicles is the fuel cell. Fuel cell power systems can be used to power passenger cars, commercial vehicles and more. Like electrolyzer manufacturers, fuel cell manufacturers can benefit from an expert supplier with an extensive portfolio.

For fuel cells, that portfolio should include high-reliability flow control, pressure regulators, safety junction boxes and flameproof cable glands. Designs should be compact and lightweight to enable manufacturers to create systems with high power density and extended cell life. Manufacturers can lower the risk of fuel cell system failure with solutions that provide stable pressure regulation, safe distribution and equipment connectivity.

Once H_2-powered vehicles populate the road, drivers will need to refuel them. As fueling stations transition to green H_2, they face sustainability, safety and maintenance challenges. One concern is accurate monitoring of H_2 flow to ensure that customers dispense the right amount of fuel every time, quickly and safely. Another is accurate maintenance of the condition of fueling stations and their critical components to ensure that stations are available for users at any given time, whether they are deployed in dense or remote areas. Fueling station equipment can leverage digital transformation to solve some of these critical challenges.

Starting at the device level, smart sensor technology and the data it provides can lay the foundation on which digital transformation is built. Building on this foundation, utilizing a programmable logic controller (PLC) with integrated edge gateway capabilities can provide complete control and turn aggregated data into real-time information/analytics of the fuel dispensing process or of the condition of the system itself.

FIG. 2. Key technology partners have a broad range of equipment for measurement and control processes.

The power of digital transformation can be scaled greatly beyond just one fueling station to a vast network of stations, where information can be aggregated to help optimize the entire network. Dispensing accurate fuel volumes at the highest flowrates safely, as well as reducing the probability of leaks and monitoring the condition of the fueling station, ensures robust operation and optimal yield.

The PLC, combined with an edge gateway, can also perform analysis and visualization of diagnostic and process data, which can be provided locally to the fuel station operator and remotely to the H_2 supplier, simplifying supply chain logistics. Having remote access to filling rates and preventive maintenance information means that H_2 suppliers are filling tanks only when necessary and providing maintenance only when needed.

From storage tanks to tube trailers to dispensers, fueling station systems must also be safe and easy to maintain, as well as meet the highest performance and regulatory standards. To reliably protect personnel, customers and property, ultrasonic gas leak detection systems continuously monitor fueling stations for ultrasound generated from the release of pressurized gas. Pressure transmitters designed for high-pressure measurement and flowmeters specifically designed for H_2 dispensing applications can accurately measure pressure and gas flow. Connecting these important devices that monitor critical parameters to a higher-layer gateway can be used to deliver real-time warnings and alerts to staff on premises or remotely, providing further safety enhancements.

The first step to sustainable success. Building the infrastructure and processes needed to transition to green H_2 requires a partner that can support companies at each stage of their scale-up. Taking a scalable approach will reduce risk while making meaningful progress.

Since green H_2 is still a relatively new business, companies must rely on partners with broad knowledge and expertise that have already proven themselves in the H_2 industry (**FIG. 2**). These expert partners already know the regulations and certifications needed and how they change, depending on the region. They likely already have a physical presence to manufacture close to customers and their markets.

Emerson, for instance, has been involved in the H_2 industry since its beginnings. Since that time, the company has developed full capabilities across the H_2 fueling value chain around the globe. We are very excited about providing innovative solutions for other new challenges as this expanding frontier presents them.

The time is now. Green H_2 is exceptionally clean and efficient, but as we have seen, building the infrastructure, controlling the gas and making it available for consumption requires expertise. Companies are better equipped to forge ahead if they partner with a specialist that already has a strong presence and relevant experience, holds deep industry and regulatory knowledge and can provide the needed solutions. This strategic partnership will give them a strong position and long-lasting competitive advantage as they make the promising future of green H_2 a reality.

SPECIAL FOCUS: PATHWAYS FOR SUSTAINABLE HYDROGEN

Technical and economic pathways for sustainable hydrogen production

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In the past few years, increased focus has been devoted to sustainable energy sources and green fuel alternatives due to a series of social, environmental and health-related concerns. This attention seems to be exacerbated during the COVID-19 pandemic and the rethinking of the way in which we live, the impact we make on the ecosystem and the implications these will have to future generations.

In addition, large corporations are witnessing how sustainable green energy companies are gaining in importance and public favor while directly affecting their bottom lines. "Sustainable energy" indicates that the production and use of the energy does not create harmful effects to people and the environment, such as emissions and waste, insensible water use, deforestation or negative impacts on animal life. This sustainable energy would be replenished at an established rate and should, in theory, be able to do so perpetually, with proper maintenance.

While fossil fuels and carbon-based energy and fuel sources still dominate the market today, alternative energy sources have experienced significant growth in recent years. Among these alternative sources of energy is hydrogen gas (H_2). This source has the potential to achieve a high level of sustainability because of its generation pathways.

H_2 production modes and sustainability. When talking about H_2, some basics must be covered in terms of its properties and environmental impact. H_2 is the most abundant element in the universe. On earth, its production can follow a number of different avenues that have been coded by "color," or production mode. The most-often-used modes are gray, blue and green, which are related to the actual H_2 production pathway in terms of carbon emissions (sometimes referred to as carbon footprint).

"Gray" H_2 production employs fossil fuels that release carbon emissions into the atmosphere primarily as CO_2 or greenhouse gas emissions (GHG). Therefore, gray H_2 is not an acceptable pathway to sustainability because of the associated CO_2 emissions. "Blue" H_2 production is similar to gray H_2 in terms of production; however, it uses carbon-capture technology to remove and sequester GHG emissions before they can enter the atmosphere.

A common route for CO_2 sequestration is reinjection into the ground; however, it can be argued that CO_2 rejection might not be a true pathway to sustainability, as CO_2 leaks from the ground can often occur. A portion of gaseous CO_2 can be safely stored and utilized in other industrial processes, but there is still a long way to go in terms of creating an effective carbon sequestration or immobilization methodology. Color-coding H_2 according to its source sometimes can be misinterpreted because of process details and post-production effects. Nonetheless, "green" H_2 should be characterized by having zero GHG emissions during its generation.

Green H_2—i.e., H_2 produced from renewable energy sources not requiring the use of fossil fuels or any other method that creates byproducts that negatively impact the ecosystem—can, in principle, have zero carbon emissions. Green H_2 can be a potential sustainable energy source if only the production aspect is considered. However, if the various steps beyond production are evaluated and the full H_2 manufacturing chain is considered, a different perspective may arise, posing a fundamental question: Will H_2 ever be truly and fully green, with zero emissions of any type? A positive answer seems difficult because green energy sources, such as hydric (water), geothermal, eolic (wind) and photonic (solar) still have carbon footprints and waste generation. For example, the production of photovoltaic (PV) cells for the conversion of light to electricity are associated with some emissions, as are H_2 storage and transmission.

A more realistic approach to the ecosystem impact characterization of energies should be based on their sustainability. Numerous color codes for H_2 production have been assigned depending on the production mode. This designation is a good initial approach; however, in some cases, it can be confusing or misleading. For example, pink H_2, produced using nuclear energy, is not considered a green energy source, nor can it be considered sustainable even though it has low GHG emissions. This is because, at some point, a nuclear facility and its components will need to be decommissioned. The process can be incompatible with, or damaging to, populations and the ecosystem. In addition, the carbon-intensive cement production process for the construction of these large facilities also should be considered as part of the total carbon footprint, in addition to a number of other factors.

As stated previously, many methods exist to produce H_2, and several are under development. However, the focus here is on methods for *sustainable* H_2 production. While most of the pathways to green H_2 are still in the earlier stages of development, some are much further along and are even in the initial stages of commercialization. At present, however, more than 95% of the world's H_2 is produced using steam reforming of natural gas (gray H_2). This process releases considerable emissions of CO_2 into the atmosphere. Blue H_2, in contrast, uses the same process in combination with carbon capture and sequestration protocols for trapping and disposing of CO_2 emissions.

The issue of sustainability is a topic of significant discussion today. However, it has not been addressed thoroughly due to its multifactor outcome affecting the human population, the ecosystem and the capacity of the environment to sustain a given activity or process with minimal or manageable detrimental effects. At some point in the near future, sustainability will need to be precisely defined, with metrics in place to truly assess the sustainability of H_2 production.

Electrolytic methods. One method for green H_2 production—and probably the most popular at the moment—is water (H_2O) electrolysis using renewable energy sources. This method breaks apart (splits) H_2O into H_2 gas and oxygen gas (O_2). On a fundamental level, this process is water-intensive with approximately 2.4 gal of water needed to produce 1.8 lb of H_2 gas, assuming minimal losses. In addition, the electrodes for the process use specific metals from mining operations that are not only water-intensive but also carbon-intensive, generating considerable waste. The overall sustainability for this method still requires improvement. FIG. 1 shows an example of a common electrolytic cell used for splitting water into H_2 gas and O_2 gas.

Pathways to obtain the most sustainable H_2 to date (green H_2) via water electrolysis generate the purest H_2 at > 99.9% purity. This process alone can be conducted using several different methods and can be carried out at numerous different geographical locations. The most important technologies for water electrolysis are alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid oxide cell (SOEC) high-temperature electrolysis. FIG. 2 shows a common scheme for a PEM electrolyzer cell. The membrane material is a key feature of PEM cell technology.

At present, water electrolysis is the most developed method for green H_2 globally and is sold commercially. A number of companies have been installing large-scale electrolyzers in different locations worldwide. The use of renewable energy coupled with water-splitting technology is how this method is considered, to a certain extent, sustainable. Nevertheless, water electrolysis is the shortest-term pathway for achieving highly sustainable H_2 production. Corporations and research groups are investigating how PEM can be used more efficiently by lowering the energy requirements for water splitting. This area of research has been more active compared to H_2 storage and transportation, which are still carbon-intensive. However, ammonia (NH_3) and other alternatives are receiving attention for their potential use as H_2 carriers. This is an area of ongoing development that is characterized by a number of challenges, starting with the fact that ammonia has an extremely pungent odor and must be first cracked at the point of use to produce nitrogen and H_2.

An alternative method for H_2 production is photo-electrochemical (PEC) water splitting. This method uses specialized semiconductors (PEC materials) and light energy to directly dissociate the water molecule into H_2 gas and O_2 gas. This technology is a long-term pathway due to present technology limitations; however, it holds significant potential for commercial use.

Furthermore, thermochemical water splitting uses high temperature from a concentrated solar power farm to split the water molecule. Water, liquid and vapor are used in this method, in addition to turbines, to create a loop that consumes only water.

Solar and wind pathways. The use of solar energy to produce H_2 can be carried out in two main ways:

1. Water electrolysis, using solar-generated electricity
2. Water splitting with direct solar energy.

When considering solar-generated electricity, PV cells to promote water electrolysis often come to mind. To be practical and for large-scale deployment, the cost of H_2 generation via solar energy must be significantly reduced. Previous studies have predicted that achieving a high solar-to-H_2 efficiency is a significant driving force for reducing H_2 generation costs.

To date, the highest efficiency using a PV water-splitting system is around 12%. Theoretical studies suggest that 25%–30% efficiency can be achieved. Solar-thermal methods via direct dissociation of water employ the high temperatures generated by solar collectors to split water molecules into H_2 gas and O_2 gas. PEC water splitting is a form of electrolysis, but direct sunlight is used to irradiate a semiconductor immersed in water, which then produces the current used to split water into H_2 gas and O_2 gas.

Solar energy is not free of challenges. The technology must overcome several hurdles to achieve better sustainability:

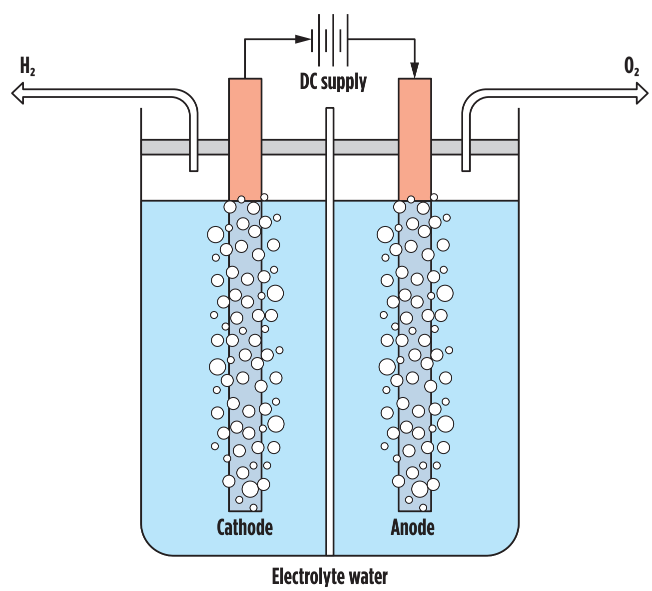

FIG. 1. Example of a common electrolytic cell for water splitting.

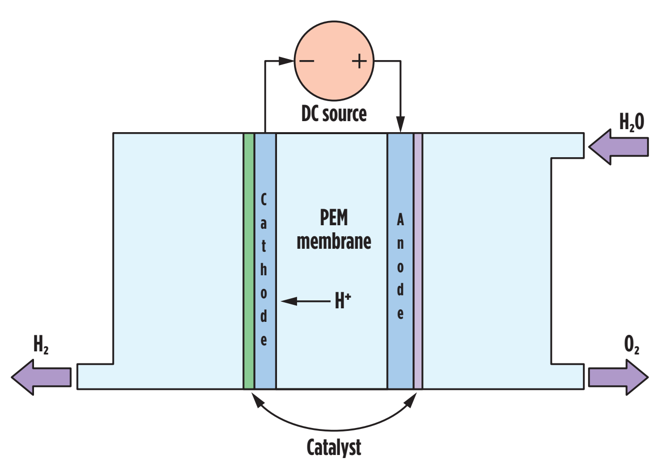

FIG. 2. Diagram of a simplified PEM electrolytic cell.

- Low light-to-energy conversion efficiency
- Large plot spaces required to assemble solar farms
- Variability of weather conditions
- Fabrication pollution.

Although contamination related to solar energy systems is less compared to other sources of energy, solar energy can produce environmental impacts related to the GHG emissions associated with panel manufacturing, transportation and installation. Additionally, certain hazardous materials and products are used during the manufacturing process of solar PV panels, which can negatively impact the ecosystem.

Wind is an abundant but variable resource for producing electricity. Wind-generated (eolic) electricity also can be used to power water electrolysis systems to produce H_2 gas and O_2 gas. Wind energy offers a number of advantages over other energy sources; however, it too must overcome several challenges. One advantage is that windpower is often a cost-effective energy pathway. When wind turbines are used onshore as opposed to offshore, they are one of the lowest-priced energy sources available today, with an estimated electricity production cost of $1/kWh–$2/kWh (after tax credits are applied).

Wind is a cleaner fuel source compared to hydrocarbons. It does not contaminate the air compared to power plants that use coal or natural gas, which emit CO_2, particulate matter, SO_x and NO_x. These emissions lead to negative effects such as acid rain, smog and greenhouse effect. Like solar energy, wind energy is considered to be a green and sustainable energy source. In fact, wind energy can be viewed as a variation of solar energy because wind is basically produced by solar heating of the atmosphere.

As long as the sun shines and the wind blows, the energy inherent in them can be harvested. However, windpower and solar energy find challenges to operating under extreme weather conditions. Wind turbines can be noisy and affect the aesthetic of a landscape. Wind farms can also impact local wildlife, such as birds and bats that may fly into moving turbine blades. Additionally, the production of wind turbine blades can be fairly carbon-intensive. The lifespan of these blades is about 15 yr–20 yr. After their lifecycle is complete, some wind turbine blades can be recycled, but others must be landfilled because they are non-recyclable.

Biological pathways. Methods employing biological avenues also have been used to create green and sustainable H_2. One method that shows potential is microbial biomass (organic matter) conversion. In this process, microorganisms break down biomass by consuming and digesting its components, releasing H_2 gas as a byproduct. This pathway is not in use commercially at present; however, research funding will likely propel the technology over the mid- to long term, and biomass conversion could see large-scale commercialization in the future.

A related method to biomass conversion is photobiological production. This process uses microorganisms in conjunction with sunlight to transform water and organic matter into H_2 gas. This pathway is still in the early stages, but it shows promising long-term potential as a highly sustainable H_2 production pathway.

Finally, certain types of algae will also produce H_2 gas as a byproduct of photosynthesis, requiring only sunlight, carbon dioxide (CO_2) and water. Researchers in algal H_2 production (sometimes referred to as "olive" H_2) are using a series of genetic modification techniques to increase H_2 production efficiency in certain algal subsets.

H_2 gas also can be produced from municipal solid waste, landfill gas, biogas and waste gas from water treatment plants. These alternative routes do not necessarily lead to green H_2 production; however, they add a certain level of sustainability to the entire process of H_2 production.

H_2 production cost implications. The cost of H_2 production in present commercial applications can vary greatly. The lowest H_2 costs are associated with non-renewable processes—predominately gray H_2 from steam methane reforming (SMR). The cost of H_2 production from SMR ranges from approximately $1/lb–$2.5/lb. Future costs using the same method will likely achieve $0.75/lb. If carbon-capture-and-sequestration equipment is in place, $0.11/lb–$0.2/lb should be added to the final cost.

Electrolysis of water in the U.S., using the local electrical grid, would produce H_2 at $3/lb–4/lb. Future costs using the same method are estimated at around $1.5/lb–$2/lb. Wind-powered water electrolysis generates H_2 at approximately $3/lb–$5/lb. Future costs using the same pathway are estimated at $1.25/lb–$1.65/lb. The cost of solar-produced H_2 via electrolysis is presently at $4/lb–$8/lb. Future costs using the same route are estimated at $1/lb–$2/lb.

At present, the cost of H_2 production from biomass pathways is approximately $2.5/lb–$3.5/lb; however, large-scale production of H_2 using biomass is estimated to cost as little as $0.8/lb–$1.5/lb in the future. H_2 production via nuclear thermal conversion of water can achieve a cost of $1.05/lb–$1.5/lb. However, nuclear-powered H_2 production technology is not presently considered to be a sustainable or renewable H_2 production pathway, and is included here only for comparison purposes.

Takeaway. Sustainable H_2 production methods pose many challenges for the future. To start, the term "sustainability" as it pertains to H_2 production must be accurately defined, and metrics should be in place to quantify the true sustainability of a given H_2 production pathway.

Most H_2 production pathways have a carbon footprint and produce an impact to the ecosystem, regardless of their assigned color. Some H_2 production pathways are more sustainable compared with others. However, to be able to claim a sustainable (or fully sustainable) H_2 production method, the complete production sequence should be evaluated—from the mining and manufacturing of the raw materials for equipment manufacturing, transportation and installation, to the H_2 production itself in addition to storage, transportation and point of use.

At present, wind- and solar-powered water electrolysis are the most sustainable H_2 pathways, despite the carbon footprints generated by the construction of their facilities. Nonetheless, H_2 is an energy source with minimal impact to the ecosystem, and it will only become greener and more sustainable with better technologies, materials and methods.

DAVID ENGEL has more than 20 yr of experience in a variety of areas of chemical engineering and chemistry. He is the inventor in 21 U.S. invention patents and the author/presenter of more than 100 technical papers and conference presentations. Dr. Engel is the Managing Director of Nexo Solutions Companies and heads the Board of Directors for Exion Systems. He holds a BS degree in industrial chemistry and a PhD in organic chemistry.

Ready-now blue hydrogen leads the way to decarbonization

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The urgency to limit global warming to 1.5°C is intensifying. Global leaders are developing decarbonization strategies to meet the goals of the Paris Climate Accord. Climate modeling indicates that to meet this ambition, rapid, aggressive decarbonization must start now, and global CO_2 emissions must reach net zero by 2050. This will require a multidimensional strategy, employing cost-effective decarbonization tools including improved efficiency, circularity, deep electrification with renewable power, migration to low carbon intensity or renewable fuels and feedstocks, and carbon capture and storage (CCS).

One challenge is the so-called "hard-to-decarbonize" sectors, such as industrial, residential and heavy transportation. Reducing emissions in these sectors requires either large-scale and distributed deployment of CCS or switching to renewable or clean-burning fuels. Hydrogen is a promising fuel because it generates no greenhouse gas emissions at the point of use. Demand for H_2 is expected to increase up to 10-fold, from 75 MMtpy today, as it replaces natural gas, diesel and jet fuel.[1]

For H_2 to be a critical vector for the energy transition in the coming decades, its production must be decarbonized. Today, H_2 is produced mainly from fossil fuels, resulting in 800 MMtpy of CO_2 emissions—2% of total global CO_2 emissions. This traditional production scheme is called "gray" H_2 and has lifecycle greenhouse gas emissions of 9–11 kg CO_2 equivalent (CO_{2eq})/kg H_2, depending on the method of production and transportation distance.[2]

Several methods exist to produce H_2 with low carbon intensity, including the addition of CCS for so-called "blue" H_2 (1.2–1.5 CO_{2eq}/kg H_2 at 90%–98% CCS rates), use of renewable feedstocks such as biogas or biofuels (1–3.3 CO_{2eq}/kg H_2), or water electrolysis using 100% renewable electricity for so-called "green" H_2 (0.3–1 kg CO_{2eq}/kg H_2). Even 100% renewable electricity does not have zero lifecycle greenhouse gas emissions because energy is required to produce wind turbines and solar panels.

All three of these low-carbon-intensity H_2 production pathways can achieve very low lifecycle emissions compared to gray H_2. Each will have a role in supplying the H_2 demands of the future, as shown by the almost daily announcements of new blue and green H_2 commercial projects and studies around the world.

The lowest lifecycle emissions cited previously are for 100% wind-powered electrolysis of water, coming in at 0.3 kg CO_{2eq}/kg H_2. Although multi-GW projects have been announced, green H_2 is an industry in its infancy, with the world's largest operating green H_2 plant having an electrolyzer capacity of 20 MW. To generate the same amount of H_2 as a typical refinery steam methane reformer (100 ktpy or 125 MMsft^{3}d) with renewable-powered electrolysis of water, approximately 50 times that electrolyzer capacity would be required (1 GW), along with an equal amount of installed renewable power.

This large amount of renewable power capacity is best used in a strategic decarbonization pathway to replace fossil power first, as it can have 2.5–6 times the decarbonization impact. Furthermore, despite significant cost reductions over the past 10 yr, green H_2 production remains expensive, at 4–6 times the cost of steam methane reforming with CCS.[3]

In contrast, blue H_2 can address the urgent challenge of decarbonization as the ready-now, commercially proven, and economic alternative to CO_2-emitting processes. The H_2 production and carbon-capture technologies that enable blue H_2 are commercially proven at scale and economical at CO_2 prices that are available in Europe and North America today. The technology is well-suited to serve existing and emerging H_2 markets.

In the near term, decarbonizing H_2 production of existing refining and chemical feedstock assets can be expedited with bolt-on carbon-capture revamps. Over the next decade, new low-carbon-intensity H_2 plants will be built to meet the steep growth in demand for clean H_2 fuel.

The main infrastructure hurdle for blue H_2 is the widespread development of carbon-sequestration facilities for permanent geological storage. Many worldwide projects are in various stages of project lifecycles, amounting to approximately 40 MMtpy of CO_2 storage capacity. By 2050, if all H_2 demand (550 MMtpy) were met by blue H_2, then the CO_2 generated will consume < 0.02%/yr of current assessed global high- and medium-confidence underground CO_2 capacity.[4] Ongoing development of CO_2 infrastructure for transportation and sequestration is needed in tandem with blue H_2 and other CCS decarbonization projects.

Blue H_2 plays an important role in leading the way to decarbonization. This article explores technology options for blue H_2 production, including the revamp of existing assets and greenfield installations. Technology selection and operating parameters have a role to play in maximizing CO_2 reduction impact while delivering the H_2 and CO_2 products on spec and at the lowest cost of production.

Existing SMR retrofit. Most existing H_2 production plants for refining, chemical and agricultural use employ a steam methane reformer (SMR) to convert hydrocarbon feeds, such as natural gas and steam, into synthesis gas, which comprises H_2, CO,

CO_2, unconverted methane and a small amount of inerts. To maximize H_2, the synthesis gas is cooled and shifted in a water-gas shift reactor to convert CO and water to H_2 and CO_2.

In a gray H_2 scheme, the shifted syngas is separated in an H_2 pressure swing adsorption (PSA) unit to generate a high-purity H_2 stream and a low-pressure tail gas stream that is sent to the reformer furnace as fuel, with additional natural gas to supply heat for the endothermic SMR reaction. Accordingly, all the carbon from the natural gas exits the system as CO_2 in the furnace stack.

To reduce the carbon emissions of an existing gray H_2 asset, CO_2 can be captured from three locations:

1. Shifted syngas
2. PSA tail gas
3. Flue gas.

The cost of CO_2 capture depends on the pressure and concentration of the CO_2 in the source stream (TABLE 1), plus the product specifications for the H_2 and CO_2. The most cost-effective location to remove CO_2 is from the pre-combustion streams. The CO_2 can be removed by a variety of means, including solvent-based absorption, PSA or cryogenic fractionation.

The option that provides the lowest overall cost of CO_2 captured is cryogenic fractionation, which also achieves additional high-purity H_2 yield (FIG. 1). In this option, the H_2 PSA tail gas is compressed, dried, condensed and fractionated, resulting in a high-purity liquid CO_2 stream. Combining separation and liquefaction in a single unit operation saves utilities when a liquid product is required.

Recent advances include further separation of the CO_2 fractionation overhead in a second, smaller PSA unit that operates with a novel process cycle that enables recovery of 90% of the remaining H_2. Overall, 99% H_2 recovery from the SMR is possible with this scheme. This additional H_2 recovery offsets investment in CO_2 capture, reducing the net cost of carbon captured to \$20/t–\$40/t. This retrofit does not require any revamp to the existing H_2 PSA, can be operated "on" or "off" without impacting the SMR operation, is solvent-free, has a smaller footprint than an amine unit, requires no steam usage in the CO_2 recovery steps, and is guaranteed to meet high-purity CO_2 product specifications with 99+% CO_2 recovery. This combination of technologies has been selected for a large U.S. CCS project for clean H_2 production at Wabash Valley Resources LLC in West Terre Haute, Indiana.

An alternative option for CO_2 capture from the PSA tail gas is a CO_2 PSA unit. A CO_2 PSA unit can be installed on the shifted syngas or the H_2 PSA tail gas, although the latter is preferred primarily due to a simpler revamp and ease of operation in the event that the CO_2 capture unit is bypassed (FIG. 2). The CO_2 PSA is the lowest CAPEX and OPEX carbon-capture option and can remove 99% of the CO_2 in the pre-combustion stream, but the extracted product is low pressure and low purity, requiring drying and liquefaction, or contaminant polishing via catalytic oxidation, followed by drying and multiple stages of compression to be transport-ready.

The third option for CO_2 recovery is amine-based solvent capture of the shifted syngas. This established technology can achieve 99% CO_2 removal from the shifted stream (FIG. 3). However, this option requires the use of steam for solvent regeneration. The carbon emissions associated with steam generation erode the net benefit. Furthermore, by removing the CO_2 upstream of the H_2 PSA, the overall H_2 recovery will be eroded. This deficit could be mitigated with PSA adsorbent reload and cycle modification; however, such changes would make it very difficult to continue operation if the CO_2 removal unit were bypassed.

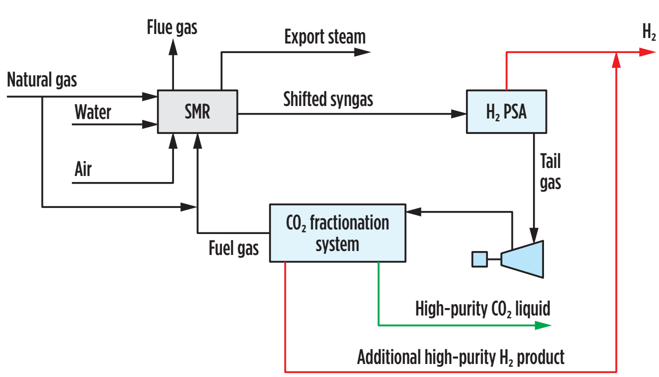

FIG. 1. SMR retrofit CO_2 capture option 1.

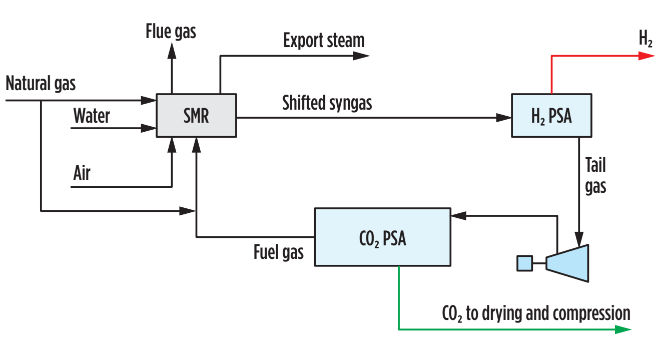

FIG. 2. SMR retrofit CO_2 capture option 2.

TABLE 1. Gray H_2 SMR process stream pressures and CO_2 concentrations

	Pre-combustion		Post-combustion
	Shifted syngas	PSA tail gas	Flue gas
CO_2 content, mol%	12%–18%	50%–60%	15%–22%
Pressure, barg	20–30	0.3–0.5	0.1

TABLE 2. Comparison of CO_2 capture options for blue H_2

	Cryogenic fractionation on tail gas	CO_2 PSA on tail gas	Amine on shifted syngas	Amine on flue gas
% CO_2 recovery from stream	> 99%	> 99%	> 99%	90%–99%
CO_2 phase	Liquid	Gas	Gas	Gas
Ultra-high-purity CO_2	Yes	No	No	No
Steam required	No	No	Yes	Yes
Burner revamp	Yes	Yes	Yes	No
H_2 yield	+10%	No change	–1%	No change
CAPEX/OPEX	Medium	Low	Medium	High
Cost of CO_2 captured, \$/t	20–40	35–50	45–60	70–100

Finally, the low-pressure CO_2 product requires drying and multistage compression or liquefaction to be transport-ready. For end-users that want gas-phase CO_2 and are long on steam, an amine unit is a reliable, proven choice for CO_2 recovery, albeit at a higher cost of capture than tail gas recovery (**TABLE 2**).

In all cases, the composition of the fuel gas recycled to the SMR furnace is significantly altered. As a result, burner revamp is required. CO_2 removal from the fuel gas requires advanced burner technology for stability and to achieve low NO_x emissions. Advanced burners are customized to the furnace licensor's specifications and can be revamped to enable low-carbon-intensity H_2 production, including the ability to rapidly switch between multiple fuels in the event the CO_2 system is bypassed.

Adding any of the three pre-combustion CO_2 removal technologies discussed to a conventional SMR unit will reduce emissions by up to 60%. For a typical refinery SMR producing 100 ktpy of H_2 (125 MMsft^{3}d), up to 520 ktpy of CO_2 can be captured, which is enough to make a significant impact in many near-term CO_2 reduction pledges.

To further reduce emissions, CO_2 must be eliminated from the furnace flue gas. Two options exist to reduce flue gas emissions:

1. Solvent-based post-combustion CO_2 absorption
2. SMR revamp options to minimize furnace firing and use of an H_2-rich fuel.

The flue gas stream is the most expensive stream to scrub CO_2 due to the low pressure and low concentration. Current best-in-class solvent technology for flue gas capture results in costs 2–4 times more per metric t of CO_2 captured than pre-combustion capture due to the low CO_2 partial pressure and solvent degradation. To reduce the cost of SMR flue gas CO_2 capture, advanced solvents with high solvent stability, improved mass transfer properties, and low heat of regeneration are needed.

Flue gas emissions also can be reduced through SMR revamp options that minimize furnace firing and use of an H_2-rich fuel. Several options can result in greater than 90% CO_2 capture without the need for expensive post-combustion capture. These options include operating the reformer at high methane conversion in a pre-reformer, a primary reformer and, optionally, a secondary gas heated reformer in series or in parallel; eliminating excess steam export; using a structured catalyst insert; adding low-temperature water-gas shift to minimize CO content in the shifted syngas; removing the pre-combustion CO_2 from either the syngas or the tail gas, and diverting a slipstream of H_2-rich fuel to the furnace.[5] These revamp options to minimize furnace firing may be invasive for existing assets, but this type of optimized SMR design that concentrates CO_2 for pre-combustion capture is expected to play a significant role for new assets.

SMR retrofit financials.

For low-carbon-intensity H_2 projects to be viable, government policy must provide a business case for investment—which can come in the form of funding, incentives, trading schemes, credits and even taxes on CO_2. Recently, CO_2 price structures, national decarbonization strategies, and public- and private-sector investments in clean energy have been seen globally.

Now is an active time for CCS in the U.S. because of the enhanced 45Q federal tax credit signed into law in 2018, with the IRS issuing final guidance in August 2020. The final guidance provides the clarity and assurance that CCS developers and investors need to move beyond the preliminary stage. The tax credit provides up to \$35/t of CO_2 for enhanced oil recovery (EOR) and \$50/t of CO_2 for permanent geological storage for CO_2 captured in facilities that meet thresholds in terms of size, and where construction begins by the end of 2025.

Another example is in the EU, where the Emissions Trading System (ETS), a cap-and-trade scheme, saw CO_2 prices rise to more than €40/t (\$48/t) in Q1 2021. These carbon prices are sufficient to make blue H_2 projects commercially attractive today. **TABLE 3** shows that retrofitting an SMR with cryogenic fractionation on tail gas can provide solid payback in both the U.S. and EU.

New blue H_2 as fuel plants.

Growth in H_2 demand is expected to come largely from its use as a CO_2-free energy source to partially displace natural gas for heat and power in industrial and

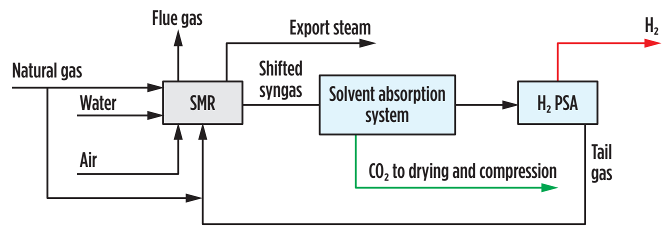

FIG. 3. SMR retrofit CO_2 capture option 3.

TABLE 3. Example financials for viable SMR retrofit projects

Cost of CO_2 captured, \$/t	U.S.	EU
Carbon capture plant costs		
Utility cost	–21	–45
Fixed cost (maintenance and overhead)	–11	–11
Annualized capital cost	–18	–18
Product values		
Value of 10% additional H_2 recovery	28	38
Total		
Net cost of carbon captured	–22	–37
CO_2 transport and storage	–10	–10
CO_2 price	50[1]	48[2]
Net value	18	1

Basis: Negative values are costs and positive values are revenues on \$/t CO_2 basis
U.S.: \$3/GJ (LHV) natural gas price; \$1.35/kg H_2 value
EU: \$6.6/GJ (LHV) natural gas price; \$1.8/kg H_2 value
[1] Tax credit in U.S. under IRC Section 45Q for carbon captured in permanent geological storage
[2] EU allowance unit trading at €40/t CO_2 in Q1 2021

TABLE 4. Selected H_2 purity specifications by end use

	For refining and chemical	For natural gas pipeline	For fuel cells
H_2 purity	99.9+%	98%	99.97%
CO, max ppmv	10	20	0.2
CH_4, max ppmv	–	–	100
O_2, max ppmv	3	2,000	5

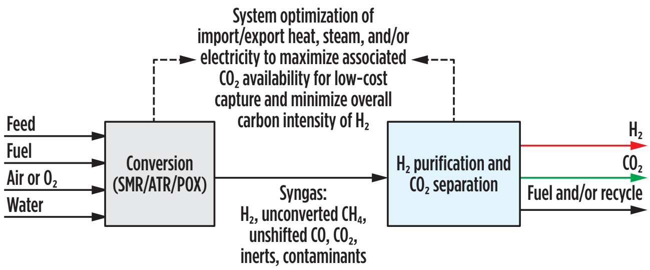

FIG. 4. New blue H_2 unit landscape.

residential sectors where gas infrastructure currently exists. Today, about 2,000 Bm^3 of natural gas is used for heat and power in a highly distributed user base. A portion of this volume can be substituted by H_2 without major infrastructure modifications while still using the distribution network for natural gas. Greenfield design of these H_2-as-fuel plants can be customized to deliver the lowest cost of H_2 production and the lowest cost of CO_2 avoided. H_2 is also expected to be used as an energy source in the transportation sector. H_2 can be used in a fuel cell to power forklifts, cars, trucks and even locomotives, ships and planes.

Each of these end-use applications requires that the H_2 meet certain purity and pressure specifications (**TABLE 4**). In the refining industry, H_2 is typically purified with PSA units that can deliver 99.9+% purity at more than 90% recovery for use in hydroprocessing, where catalysts are sensitive to CO poisoning. For use in ammonia synthesis, the syngas typically is scrubbed of CO_2 and then methanated and washed with nitrogen, or purified by PSA.

In the emerging fuel cell markets, ISO 14687 sets specifications for H_2 fuels for fuel cells requiring 99.97% H_2 purity, 0.2 ppmv CO maximum and 5 ppmv O_2 maximum. An industry standard does not yet exist for H_2 used in natural gas networks. The Hy4Heat program in the UK conducted a cost-benefit analysis in 2019 and proposed an H_2 purity specification for domestic and commercial heating applications of more than 98% purity, a CO max of 20 ppmv in line with short-term exposure limits, and an O_2 max of 0.2% to reduce corrosion rates and maintain pipeline integrity.[6]

Similarly, the captured CO_2 product must meet certain phase and purity specifications based on its sequestration or utilization. CO_2 pipelines for enhanced oil recovery require injection pressures of 153 bar at ambient temperature, but only a fraction of all CO_2 capture sites will have direct access to a CO_2 pipeline. Many will need to transport the CO_2 to injection sites—either for pipeline transport or for geological storage. In these cases, liquid phase ship transport of CO_2 (7 bar and –50°C) is often required. Some sequestration sites have adopted strict purity specifications with ppm level limits on CO, O_2 and H_2S.

Blue H_2 producers aiming for carbon intensities approaching that of green H_2 will need to choose among SMR technology that is optimized to minimize radiant firing while using H_2-rich fuel, autothermal reforming (ATR) and partial oxidation (POX). The latter two technologies offer a similar advantage to the optimized SMR design of enabling more than 90% CO_2 capture without costly, post-combustion capture, but they achieve this by eliminating the furnace and its associated flue gas at the expense of requiring pure O_2 as a reagent and reduced production of H_2 per mole of methane processed.

In all three of these options, greater than 90% CO_2 capture can be achieved with a single capture step on a pre-combustion stream. The CO_2 capture technologies covered in the SMR retrofit analysis are equally applicable for new unit installations, irrespective of reformer selection. The most appropriate pre-combustion technology for carbon capture and H_2 purification will depend greatly on the required phase, purity, pressure, storage and means of transport for both the CO_2 and the H_2 (**FIG. 4**).

Takeaway. Hundreds of companies and countries have committed to achieving net-zero emissions in support of the Paris Climate Accord. Retrofitting existing SMR assets with carbon-capture technology is a ready-now, commercially proven and significant step on the journey to net zero. With technology innovations such as the cryogenic fractionation system on the PSA tail gas with additional H_2 yield leading to a cost of carbon captured as low as \$20/t of CO_2, these projects make financial sense today in many areas with an established price on carbon.

As the decade progresses, new blue assets in the form of SMR, ATR and POX will be built to realize the potential of H_2 to address "hard-to-decarbonize" sectors. Escalating the carbon price, coupled with emerging technological advances, will drive investment. Depending on the end uses of the H_2 and CO_2, the technology of choice for the syngas separation will vary. Through thoughtful pairing of carbon capture and H_2 purification technology, economic differentiation can be achieved, delivering a significant step in the CO_2 countdown to net zero.

LITERATURE CITED

1 Hydrogen Council, Study Task Force, "Hydrogen scaling up: A sustainable pathway for the global energy transition, 2017, Online: https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf

2 Hydrogen Council, "Hydrogen decarbonization pathways: A life-cycle assessment," 2021, Online: https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf

3 International Energy Agency, "The future of hydrogen," 2019, Online: https://www.iea.org/reports/the-future-of-hydrogen

4 Page, B., *et. al,* "Global Status of CCS 2020," Global CCS Institute, 2020, Online: https://www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf

5 Jakobsen, D. and V. Åtland, "Concepts for large scale hydrogen production," Master's thesis, Norwegian University of Science and Technology, 2016, Online: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2402554

6 DNV GL, Department for Business, Energy and Industrial Strategy, "Hy4Heat (WP2) Hydrogen purity and colourant hydrogen purity—Final report," No. 10123173, Rev. 05, 2019, Online: https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5e58ebfc9df53f4eb31f7cf8/1582885917781/WP2+Report+final.pdf

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Transforming Texas into a global hydrogen hub

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The global shift to decarbonization, earlier catalyzed by the Paris Accord and the related realization of the imperative to limit future global warming, has accelerated. The COVID-19 pandemic has raised awareness of the relationship between economic activity, energy consumption and the environment. The presently carbon-intensive energy system must be decarbonized to meet the dual challenges of expanding energy demand and producing cleaner energy. The potential for economic recovery stimulus through investment in clean energy infrastructure has been embraced by multiple regions and nations. The US is among them, upon the election of President Joe Biden and his stated priorities and initial actions to move toward a less carbon-intensive energy system.

These global and national trends overlay Texas energy transition imperatives, and perhaps surprisingly, the state's new opportunities. An expanded hydrogen economy is one option among other, interrelated, low-carbon leadership opportunities that include increased application of carbon capture, use and storage (CCUS), expanded electrification and further penetration of renewable power.

Moreover, an expanded Texas H_2 sector would leverage multiple aspects of existing energy system infrastructure and other Texas resources. Additionally, H_2 system expansion would take advantage of the state's significant labor, corporate, and academic institution capabilities, enabling the delivery of capital-intensive commodities to global customers both safely and cost efficiently.

The Center for Houston's Future and the University of Houston, with support from other key collaborators, conducted assessments to identify opportunities for expanding clean H_2 value chains in Texas and to develop a vision and roadmap to enter and expand new markets for H_2. The institutions looked beyond the considerable existing H_2 production and use in the Houston Gulf Coast region, which is predominantly used for oil refining and petrochemical feedstock. The purpose of this article is to summarize the outcomes of that work.

Hydrogen's role in decarbonization. The push by many regions and nations to develop decarbonization plans has increased the focus on the unique and multiple potential roles of H_2 in a low-carbon energy system (FIG. 1).

Since the start of 2020, multiple regions have developed strategies to use H_2 in achieving decarbonization goals, including the European Commission and several European countries (Germany, the Netherlands, Norway, Portugal, Spain and France).

Preeminent energy companies, including Shell, BP and Repsol, have also made low-carbon commitments and announced plans for H_2 projects to help meet their commitments. Such plans help explain why substantial growth in the market for H_2 gas and related equipment, such as electrolyzers and fuel cells, is projected by the Hydrogen Council at \$2.5 T by 2050.

Today, most H_2 is manufactured using natural gas (or in some regions, coal) to provide methane input for steam methane reforming (SMR). H_2 is stripped in the process, creating CO_2 as a byproduct. H_2 produced in this manner is known as gray H_2. When gray H_2 production is coupled with CCUS, it is termed blue H_2.

An alternative pathway to creating H_2 is via electrolysis of water, splitting a water molecule into H_2 and O_2. When such electrolysis is powered with renewable energy, such as wind or solar, the H_2 produced is known as green H_2. FIG. 2 illustrates these two primary H_2 pathways.

The preferred path, or combination of paths, to achieve the required rampant expansion in H_2 will vary by region. Industrial areas with existing refining operations and petrochemicals production (e.g., the Netherlands, Germany and the U.S. Gulf Coast), which currently produce extensive H_2 through SMR technology, will look to exploit their existing infrastructure to create blue H_2. Less industrialized countries and those without indigenous fossil resources will likely either import H_2 or seek

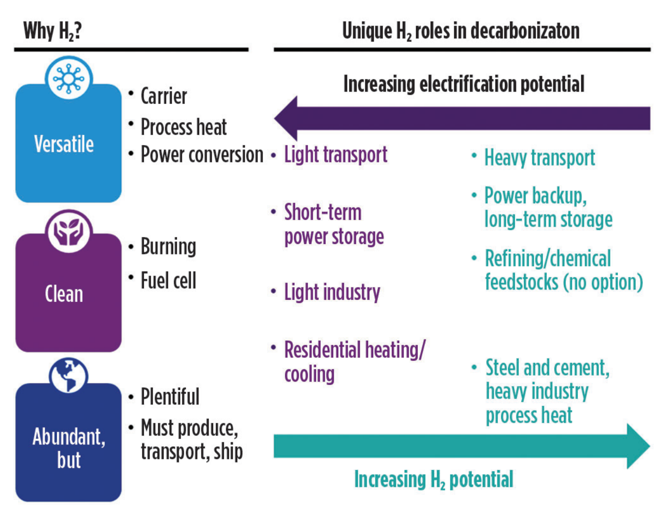

FIG. 1. Hydrogen's unique advantages and critical roles in decarbonization.

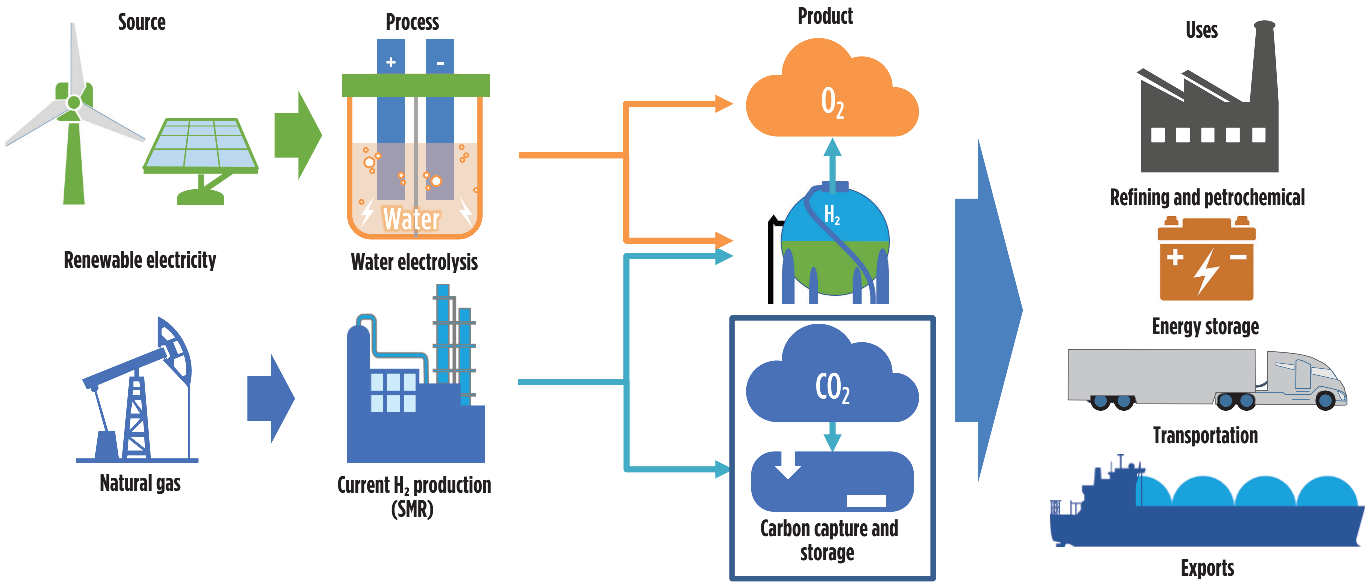

FIG. 2. Typical H_2 production options and uses.

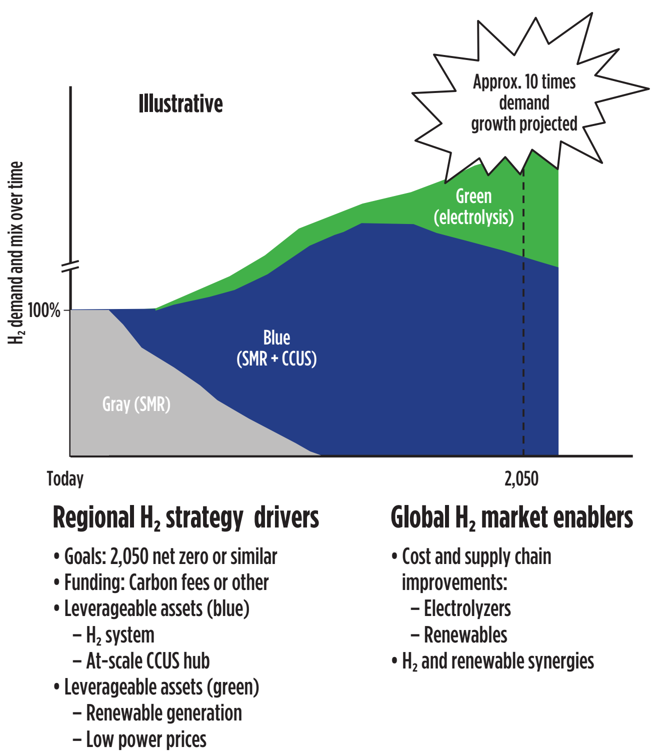

FIG. 3. Strategy and drivers for a mixed H_2 production system.

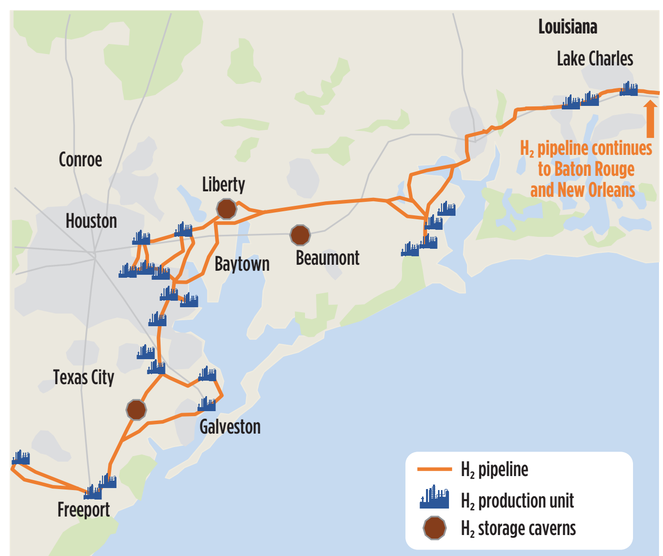

FIG. 4. Existing H_2 system in the U.S. Gulf Coast region. Sources: H2Tools, USDOT–PHMSA, Air Liquide, Air Products, Praxair.

to develop green H_2 chains to the extent that renewable energy resources are available.

Emerging regional and country strategies, therefore, typically focus on the relative role and timing of two factors:

1. Evolving from an existing gray H_2 to a blue H_2 system
2. In parallel, developing a green H_2 system.

An illustration of such an H_2 mix strategy, as well as the drivers for how such a strategy would be customized by region, are shown in FIG. 3.

Texas' role in the H_2 economy. The Texas Gulf Coast area anchors the world's leading H_2 system, producing approximately one third of U.S. total H_2 gas per year. The system encompasses an expansive network of 48 H_2 production plants, more than 900 mi of H_2 pipelines (more than half of the U.S. H_2 pipelines and one third of H_2 pipelines globally), as well as geologically unique and at-scale salt cavern storage (FIG. 4).

Today, this system primarily serves the U.S. Gulf Coast's refining and petrochemical industry. By leveraging this system through coupling gray H_2 production with CCUS, there is the potential to bring substantial volumes of H_2 to new markets rapidly and at scale.

The eastern portion of the U.S. Gulf Coast H_2 system overlays existing CCUS infrastructure—the Denbury system, which was developed to bring CO_2 to recover oil reserves

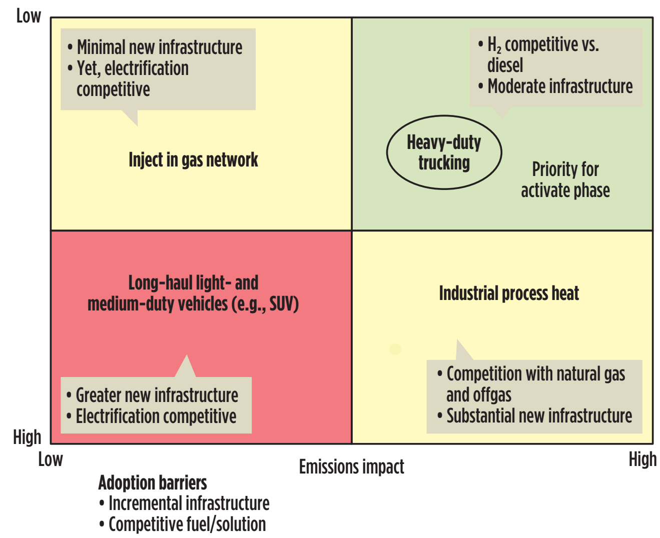

FIG. 5. Initial prioritization of blue H_2 markets.

through enhanced oil recovery (EOR). Several large SMR facilities are proximate to the Denbury system and could be linked to it via pipeline to initiate the move from gray to blue H_2. Over time, a CCUS system could be expanded, tapping into additional active and depleted reservoirs throughout the U.S. Gulf Coast both onshore and offshore. This CCUS system potentially could be expanded into the Permian basin with its vast extent of active and depleted reservoirs.

Creating new H_2 market infrastructure. There is a need to match the development of clean H_2 with an end-use market. Multiple market applications exist for H_2 beyond its existing primary uses in oil refining and as petrochemical feedstock. Here, new H_2 market opportunities are prioritized based on the extent of new infrastructure needed, the competitiveness of H_2 over existing fuels or other clean alternatives (e.g., electrification) and the relative emissions reduction (**FIG. 5**).

It was concluded that heavy trucking should be an initial priority to investigate in Texas. Trucking requires limited new infrastructure to utilize H_2 as a fuel, and H_2 fuel competes with relatively expensive and relatively higher-emitting diesel fuel. The advantages of H_2 fuel cell power in this application are many: low weight, fast refueling, high range and relatively low new infrastructure costs. Additionally, the speed of refueling, as well as range and torque requirements, favor H_2 over batteries in the heavy trucking application. Emissions still would be lower than diesel, even if the H_2 fuel was gray H_2. As gray H_2 is paired with CCUS to create blue H_2, the emissions benefit of using H_2 fuel increases.

Heavy trucking was validated to be particularly attractive as an initial new market by modeling H_2 economics relative to diesel in specific trucking corridors in Texas. Several high-concentration trucking markets involve the Houston and Houston port areas, Dallas (which is a regional distribution hub) and San Antonio (which ties into shipping from Mexico). Tapping high-density corridors minimizes the infrastructure required to achieve meaningful scale regionally, thereby improving the economics of market entry and expansion.

FIG. 6 illustrates the potential economics of the Interstate-45

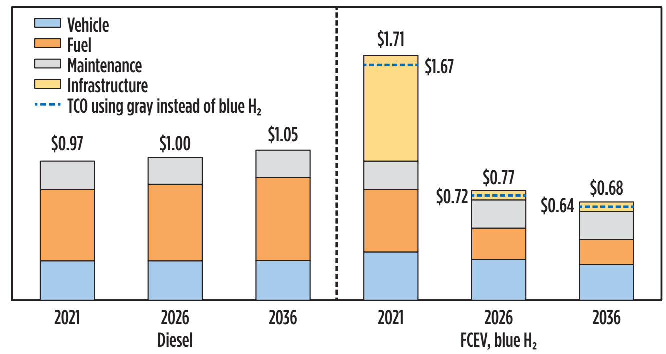

FIG. 6. Total cost of ownership for diesel vs. H_2 heavy-duty trucks on the I-45 Houston–Dallas corridor, $MM/truck. Sources: ANL, HDSRAM, ICCT, EIA.

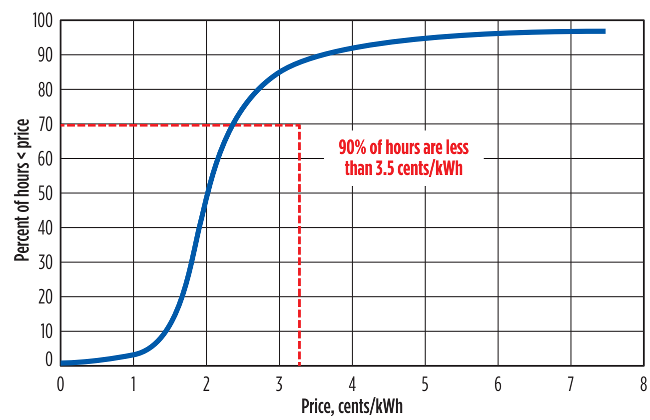

FIG. 7. Houston wholesale power price duration curve. Source: ERCOT.

(I-45) highway corridor connecting Houston with Dallas. A DOE-funded, low-emissions planning study is underway for this corridor by the North Texas Council of Governments. As with analogous markets, such as the Port of Los Angeles, economics are favorable for the I-45 corridor at scale vs. diesel fuel. Coupling this potential with the facts that vehicle manufacturers such as Nikola, Toyota and Hyundai are developing and piloting the manufacture of H_2 trucks, and shippers are increasingly seeking to curb their emissions, there is promise that this could be an early new H_2 market in Texas.

Adoption of H_2 as a fuel at the Port of Los Angeles and other geographies has been catalyzed by incentives to update truck fleets to lower-emissions fuels and to build infrastructure. Incentive requirements would be less in these scenarios, given the Texas region's present H_2 production and dense heavy-trucking patterns. Therefore, it was concluded that demonstration pilots to produce H_2 to power fuel cells can be set up over the next few years, taking advantage of the confluence of the existing low-cost, high-scale U.S. Gulf Coast H_2 system to supply proximate heavy-duty trucking corridor demand.

Initiating green H_2 value chains. As outlined in the previous sections, clear opportunities exist to bring gray and blue H_2 to market at scale quickly in Texas, and potentially for export to other regions. Doing so would accelerate decarbonization efforts while green H_2 value chains—requiring additional renewable power and electrolyzer capacity—are developed.

The region and the state hold significant advantages to incubate green H_2, which is produced via splitting a water molecule through electrolysis to create zero-emissions H_2. An important advantage, given the significant power consumption requirements for electrolysis, is that the Texas power market includes many hours of low-priced power due to a generation mix heavy in windpower (Texas is the number-one windpower-producing state), as well as a rapidly growing solar fleet. **FIG. 7** demonstrates the effects of this extensive renewable power base on the availability of very low-price power hours. Given the high-power consumption presently required for the production of H_2 via hydrolysis, low power prices create an advantage.

H_2 produced during low-cost hours can serve as long-duration H_2 storage (i.e., H_2 serves as a mechanism to store energy during periods of high renewable power input such as sunny days or weeks and provides power during periods of shortage such as cloudy days or days with no wind).

Moreover, coupling H_2 salt cavern storage, uniquely prolific in the Houston Gulf Coast area, with low-priced power creates the further opportunity to use H_2 in (even greater duration) seasonal storage (i.e., H_2 serves as a mechanism to store energy during periods of low-cost power in the winter, to be used during peak power prices in the summer). **FIG. 8** and **FIG. 9** illustrate the expected growth in Texas renewable power and additional low-price hours, as well as the synergistic role of H_2 as a storage medium as power intermittency issues rise with more renewable power on the Texas grid.

Activating blue and green H_2 opportunities. Four key initiatives are recommended to activate blue and green H_2 opportunities in the Texas region:

- Launch a heavy trucking pilot
- Expand the connection of the existing SMR system to CCUS to create blue H_2
- Pilot seasonal storage leveraging U.S. Gulf Coast H_2 caverns and low-price power
- Advance additional long-duration (> 6 hr, multi-day) H_2 storage opportunities across the Texas electrical grid.

These activation initiatives will require approximately $565 MM over 10 yr, appropriate policy changes and public funding to help defray the costs of new infrastructure build-out, equipment changeout and facilitating permitting. Applying CCUS to produce blue H_2 as a fuel could be incentivized both by CCUS policy (e.g., the federal 45Q tax credit, possibly with enhancements), as well as by a potential clean fuels incentive. Other incentives and policy changes will be needed over time to further develop new chains and markets for H_2.

Expansion phase for H_2 exports. Potential opportunities exist to expand blue and green H_2 production in the region, as clean H_2 demand continues a sharp increase through 2050. Additional market uses beyond heavy trucking include industrial process heat, electric power production and building heating—all of which exist in large quantity in the region. As H_2 system costs continue to improve, potentially accelerated through policy incentives and support, the potential for additional market opportunities grows as the comparative economics of H_2 vs. the existing fuel or energy solution improves, and infrastructure costs are amortized over increasing scale.

Many markets, domestically and globally, will need more H_2 than they can produce over the next decade to meet decarbonization goals. Some markets, domestic and international, will need to import H_2 to meet demand. A strong case exists for the Houston Gulf Coast to become a global blue H_2 exporter with its world-scale, in-place H_2 production capacity; low-cost natural gas feedstock; opportunity to create a low-cost, at-scale CCUS system; and global H_2 storage and transport infrastructure.

For example, a promising, early blue H_2 opportunity for Houston could be exporting to California to take advantage of the latter state's Low Carbon Fuel Standard incentive. A blue H_2 system, anchored in the Texas Gulf Coast area, could expand to become a major H_2 exporter, leveraging its low cost, existing scale, and advantaged pipeline and shipping positions. This could be a mid-term strategy to accelerate at-scale volumes of clean H_2 to domestic and global markets. Initial export markets may include domestic trucking markets beyond California or international markets, such as the Netherlands,

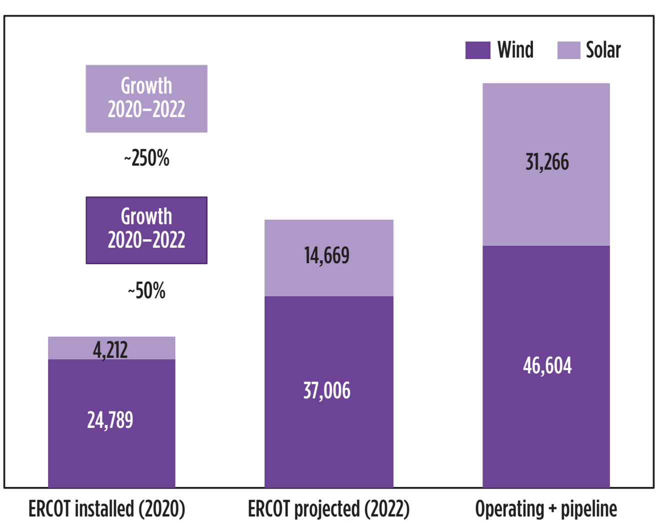

FIG. 8. ERCOT installed and potential wind and solar capacity, MW. Source: ERCOT.

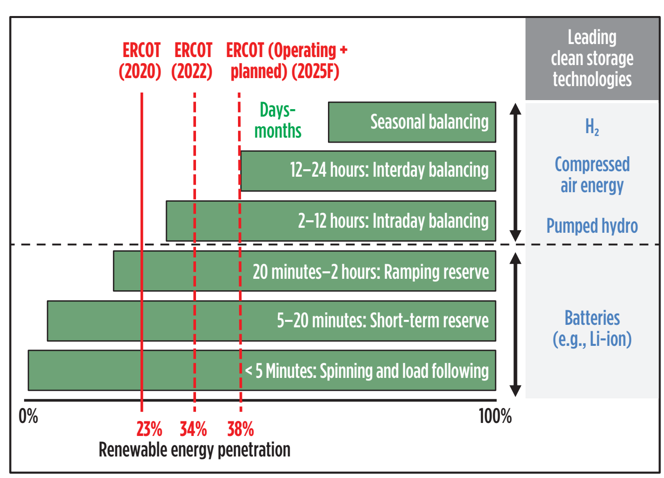

FIG. 9. Energy storage requirements vs. renewable energy penetration levels. Source: ERCOT.

Germany or Japan, which have regional supply projections short of demand requirements.

Capturing full value from new H_2 market opportunities (assuming incentives for clean H_2) will likely require leveraging the existing SMR system and, potentially, creating new methane-based H_2 production paired with CCUS.

New blue H_2 production with even lower net emissions could be realized through constructing plants with alternative technologies, such as autothermal reforming (ATR), as is planned in the Netherlands' Port of Rotterdam and UK Humber areas, and/or incorporating biomass feedstocks.

> **Leveraging world-class H_2 infrastructure and people skills, Texas can emerge as a leading global H_2 hub, driving lower emissions and bridging old and new energy systems to continue energy leadership.**

Building out the required CCUS system would likely occur in phases:

1. Activate CCUS by filling the Denbury pipeline system with CO_2 captured from eight large SMR plants in the Houston Metropolitan Statistical Area (MSA), proximate to the Denbury
2. Expand CCUS capacity, as needed, by building additional CO_2 pipeline capacity to exploit CO_2 usage and storage opportunities along the Texas Gulf Coast and extending into the Permian.

An expanded role is envisioned for green H_2 as renewable power penetration increases, as electrolysis costs and production efficiencies improve, and as policy and market trends evolve. Green H_2 could be readily integrated into the existing Gulf Coast storage, shipping and other infrastructure systems.

Rollout of Texas' H_2 plans. The outlook for a "rollout phase" is uncertain and depends on multiple forces that will significantly shape the demand, pace and source of H_2 in decarbonization. For example, public policy changes, investor preferences, renewables and electrolysis technology and cost trends could accelerate green H_2 to playing a larger role, sooner.

On the other hand, decarbonization goals and timing, CCUS technology and uptake trends, and public carbon policy could extend the role of blue H_2 in meeting rising global decarbonization needs. At present, the estimated H_2 cost of coupling SMR production with CCUS is significantly cheaper than green H_2 in the Houston region due to existing SMR H_2 infrastructure, low natural gas feedstock costs, and the opportunity to leverage and extend existing CCUS infrastructure (**FIG. 10**).

Gray and blue H_2 is also widely available at present, while green H_2 is not. However, electrolysis investment costs and efficiency are projected to improve significantly as manufacturing increases and technology advances. These factors, along with the previously mentioned renewable power availability, price reductions and other forces, could spur additional green H_2 at lower cost (**FIG. 11**).

Longer-term decarbonization opportunities. A key decarbonization opportunity is the U.S. Gulf Coast region's vast industrial sector, which comprises approximately 30% of U.S. refining capacity and more than 40% of U.S. petrochemical capacity.

The region's industrial sector accounts for 40% of Texas' industrial emissions, totaling 65 metric MMtpy. Other regions, such as Rotterdam in the Netherlands and Humber in the UK (**FIG. 12**), have developed plans to use H_2 to decarbonize industrial process heat and power by burning H_2 instead of fossil fuels. Adapting infrastructure to burn H_2 requires substantial investment. The Netherlands and the UK have instituted carbon taxes, along with public funding, to support private investment.

The Texas region has an opportunity to emerge as a leading global H_2 hub. An emerging view across many industrialized regions with H_2 plans suggests a larger role for blue H_2 through

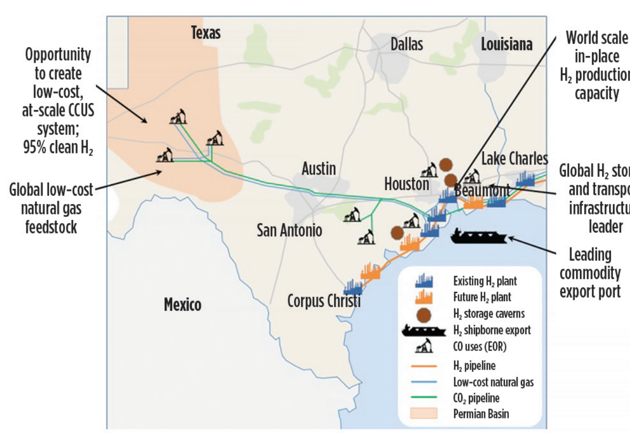

FIG. 10. Case for Houston as a global blue H_2 exporter.

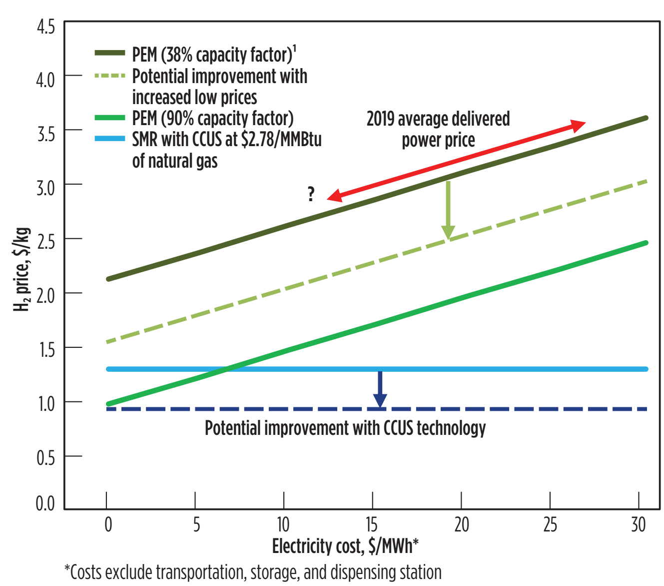

FIG. 11. Current blue and green H_2 production costs in Houston. Source: S&P Platts.

the medium term—now through the 2030s or 2040s, while at the same time accelerating green H_2 development. The timing and extent of low-carbon policy could change overall H_2 demand and the mix of blue H_2 vs. green H_2.

Cost-competitive green H_2 with scale volume potential is anticipated to emerge in the 2030s and beyond as electrolysis costs and technology improve, as fuel-cost manufacturing and scale economies improve, and as more ubiquitous and low-cost renewable power is available.

The substantial demand for clean H_2 in the near and medium term, favoring blue H_2, followed by improving and expanding green H_2 opportunities, presents a unique opportunity for the Texas region. Leveraging its world-class H_2 infrastructure, personnel and corporate assets, Texas can globalize its H_2 leadership and emerge as a leading global H_2 hub, driving lower emissions and bridging between old and new energy systems as a path to continue energy leadership, economic expansion and job growth (**FIG. 12**).

To tap this longer-term potential—as blue and green H_2 technologies and costs advance and macro-policy goals regarding decarbonization take shape—additional and adaptive policies and funding mechanisms will be required. Early establishment of these policies would help the Texas region keep pace with decarbonization initiatives in other parts of the world.

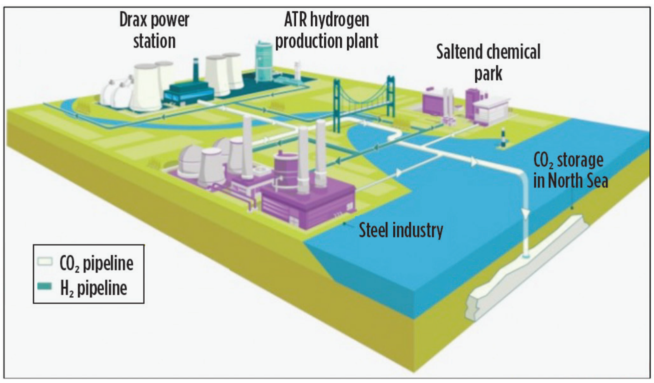

FIG. 12. Schematic of Humber, UK industrial area. Source: Equinor.

Takeaway. Research commissioned by The Center for Houston's Future and the University of Houston shows that Texas has a significant opportunity to both reduce its carbon emissions from existing H_2 production while creating new market opportunities from the energy transition (**FIG. 13**).

Furthermore, the opportunity exists to globalize Texas H_2 leadership. There is no question that the energy system is changing; the issue is whether Texas will transition rapidly enough to capture its potential. This report shows the path forward.

ANDY STEINHUBL serves as Vice Chair of the Board and sits on the Executive and Nominating Committees of the Center for Houston's Future. He recently retired with more than 35 yr of energy experience, having launched and led KPMG's U.S. Energy and Chemicals strategy group. Prior to joining KPMG, he worked for Booz & Co., where he served as the Houston office's Managing Partner and in a variety of North American and global energy sector leadership roles. He began his career at ExxonMobil. At present, Mr. Steinhubl is collaborating with the Center for Houston's Future on a variety of projects regarding Houston's role in the energy transition, including the role of H_2 in the decarbonization of Houston's energy system. Mr. Steinhubl earned a BS degree in chemical engineering at Purdue University and an MBA degree from Stanford University's Graduate School of Business.

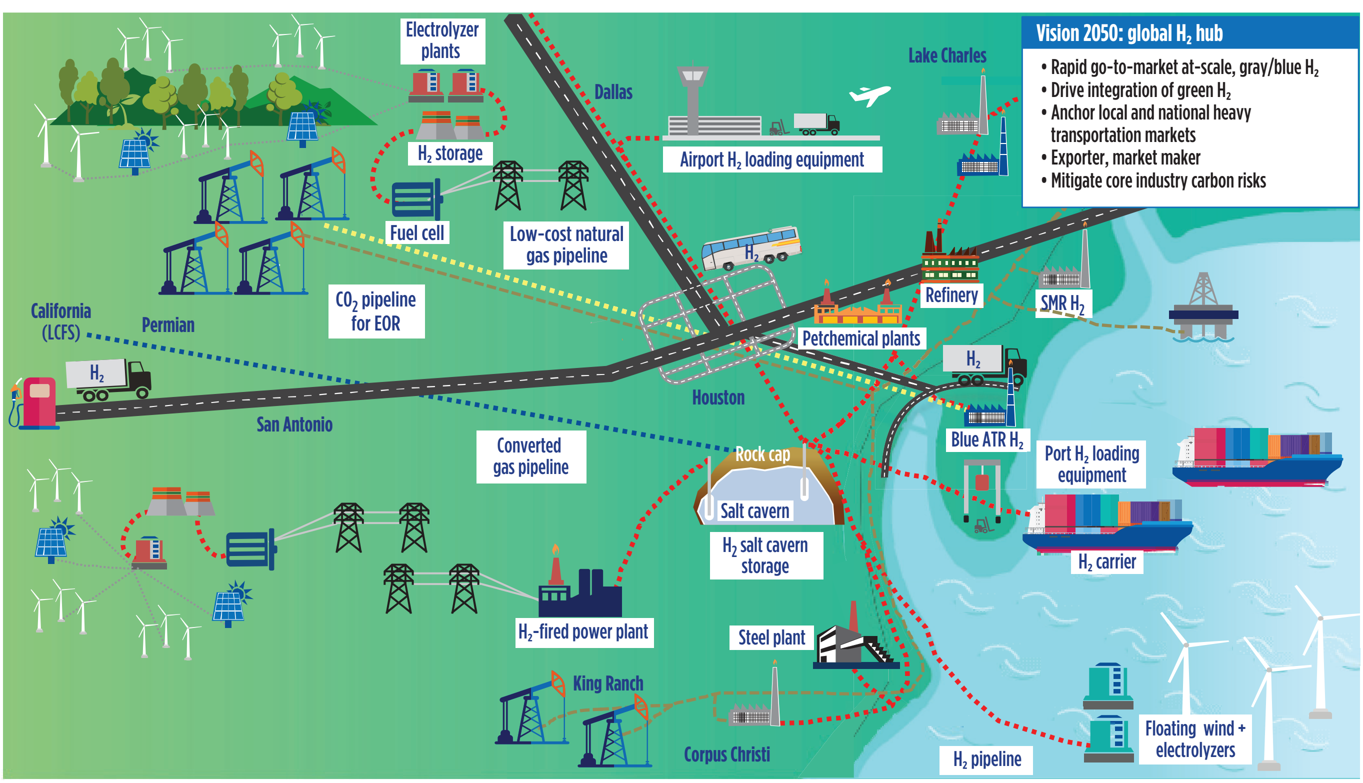

FIG. 13. The 2050 vision for a Texas H_2 economy.

Emissions-free production of blue H_2 for efficient transportation and decarbonization

T. R. REINERTSEN, REINERTSEN New Energy, Trondheim, Norway

Hydrogen production from gas, oil and coal has a reputation for being dirty and inefficient. At present, the majority of the world's H_2 is produced and used in oil refineries and chemical plants. Large emissions of CO_2 and other gases come from two main sources in these plants—steam methane reforming (SMR) and the downstream treatment of the synthesis gas, or syngas (**FIG. 1**).

Existing plants may be retrofitted to capture CO_2 from reformer flue gas and by separating CO_2 from syngas. However, the overall CO_2 capture rate will be lower than 90%, and the costs of these methods are generally high.

Over the last few years, the industry has developed new process solutions for H_2 production. In these new concepts, SMR is often replaced by autothermal reforming (ATR), with no direct emissions to the atmosphere. However, CO_2 emissions from the overall process are still at least 5%–10%.

Zero-emissions blue H_2. REINERTSEN New Energy has developed a new process, HyPro-Zero, that gives H_2 production with close to zero emissions. The process is based on existing technology in a new process flow (**FIG. 2**). It encompasses ATR and, optionally, a gas-heated reformer (GHR) fed with O_2.

Following the water-gas shift (WGS), the syngas is separated by palladium membrane technology. The palladium membrane separator is developed by subsidiary HYDROGEN Mem-Tech AS. The HyPro-Zero process achieves a very high CO_2 capture rate of 98%–99%. The purified H_2 produced complies with fuel cell quality requirements. The CO_2 is produced by cryogenic separation to a quality standard that is ready for transportation and storage.

Competitive H_2 production. The HyPro-Zero process facility is projected to have a reduced CAPEX of 25% compared to existing process solutions. The production cost for H_2 from natural gas is estimated at €1.5/kg H_2–€1.7/kg H_2, based on a natural gas price of €0.12/sm^3 and including the capture, transportation and storage of CO_2 (**TABLE 1**).

This cost estimate is significantly less than other solutions available. At present, blue H_2 can be produced at a cost of 50% or less than the cost of green H_2 via electrolysis with renewable power. The gas energy efficiency is high, at approximately 80%. Furthermore, blue H_2 can be produced at much higher volumes than green H_2—typically 100 times more per plant.

CO_2 storage. Available CO_2 storage or utilization is a prerequisite for the production of emissions-free blue H_2. CO_2 is stored onshore and offshore in Norway, the U.S., Canada and several other countries.

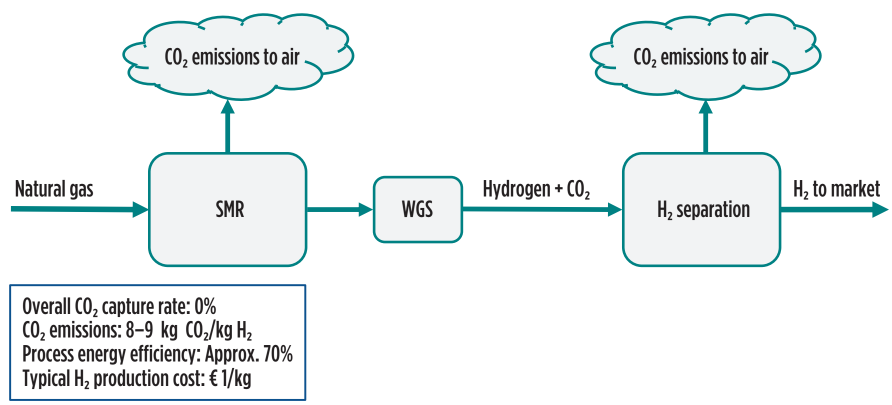

FIG. 1. Conventional production of gray H_2 (high emissions).

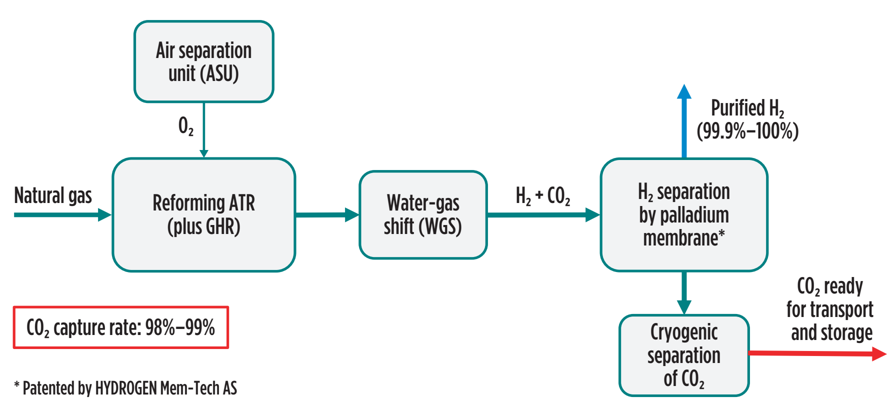

FIG. 2. A new process for large-scale, emissions-free production of H_2. Patent pending by REINERTSEN New Energy.

Recently, Norway decided to build a large CO_2 storage facility, referred to as the "Northern Lights" project (**FIG. 3**). CO_2 captured from industry and blue H_2 production facilities in Norway and other European countries will be transported by ship or pipeline to a CO_2 terminal on the coast of Norway. From the terminal, the CO_2 will be piped offshore and then injected into a subsea reservoir. The initial investment and operation costs for the Northern Lights project are estimated at €2.5 B.

Transportation of H_2. A major challenge for the market penetration of H_2 is the high cost for distribution and storage. Compressed and liquified H_2 contained in tanks is not very cost-efficient due to the low density of H_2. Decentralized, small- and medium-scale production of green H_2 might be advantageous in such cases.

However, centralized, large-scale, blue H_2 production and transportation in large-diameter pipelines is very cost-efficient. As an example, the author's company has studied the production of blue H_2 for the European market, based on Norwegian natural gas. The study examined whether the H_2 should be produced in Norway close to CO_2 storage and then transported in existing or new gas pipelines, or if the H_2 production plant should be located close to the market and the CO_2 returned to a storage facility. Three alternatives are illustrated in **FIG. 4.**

The option on the left in **FIG. 4** shows an existing pipeline, Zeepipe 2B/Europipe 1 (40 in., 924 km), redesigned from natural gas to H_2 service. The middle option shows the construction of a new, 42-in., 800-km H_2 pipeline to transport 3.5 MMtpy of H_2. The option on the right assumes a large-scale H_2 plant based on Norwegian gas, placed in the Netherlands or Germany, along with a CO_2 return line (34 in., 800 km) to a Norwegian storage facility.

Estimated costs for the three alternatives show that the cost of transporting large volumes of H_2 to the EU is very low for all cases, at less than €0.08/kg H_2. Estimates for the pipeline transportation cost are based on a novel H_2 pipeline design that allows the use of existing subsea pipelines with a minor reduction of design pressure. The author's company carried out the original design of the Zeepipe 2B gas pipeline and used this knowledge to theoretically redesign the subsea pipelines for high H_2 pressure and flow. Other European studies indicate approximately the same potential for H_2 distribution networks.

The total production and transportation cost for Norwegian blue H_2 to Europe is estimated at approximately €1.7/kg of H_2. Although some costs (financing costs, contingency costs, etc.) are not factored, the estimated result promises a competitive, clean energy solution for the energy transition in Europe and elsewhere.

Major markets for blue H_2. Future markets for blue H_2 solutions are regions with access to natural gas and geology for CO_2 storage. Other regions that presently import fossil energy may be importing H_2 in the future. Long-distance pipeline

TABLE 1. Estimated costs of large-scale, competitive blue H_2 production and transportation

Cost item	Estimated cost
H_2 production cost (including CO_2 capture)[a]	€1.2/kg of H_2
CO_2 transport and storage cost	€0.3–€0.5/kg of H_2
Total production cost	**€1.5–€1.7/kg of H_2**
Hydrogen transportation from Norway to Germany/the Netherlands	€0.08/kg of H_2
Total production and transportation cost[b]	**€1.7/kg of H_2**

[a] Natural gas price assumption: €0.12/sm³
[b] Net cost, excluding financing cost, contingency cost, etc.

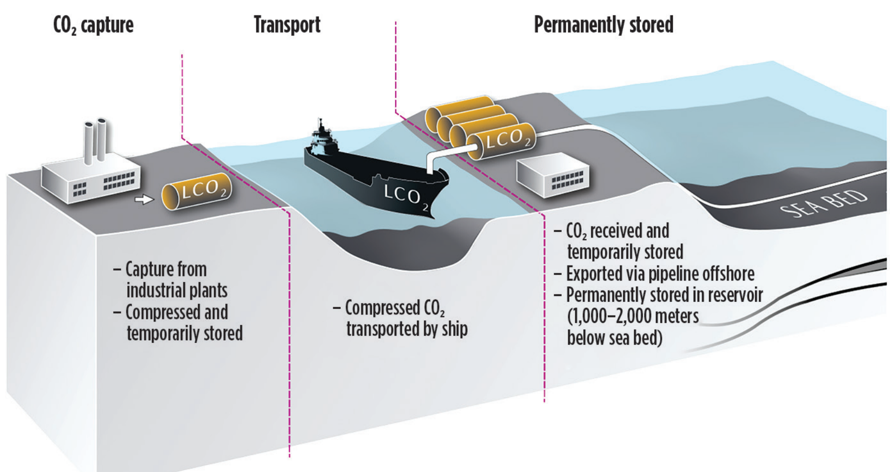

FIG. 3. Northern Lights CO_2-capture project details. Source: Equinor.

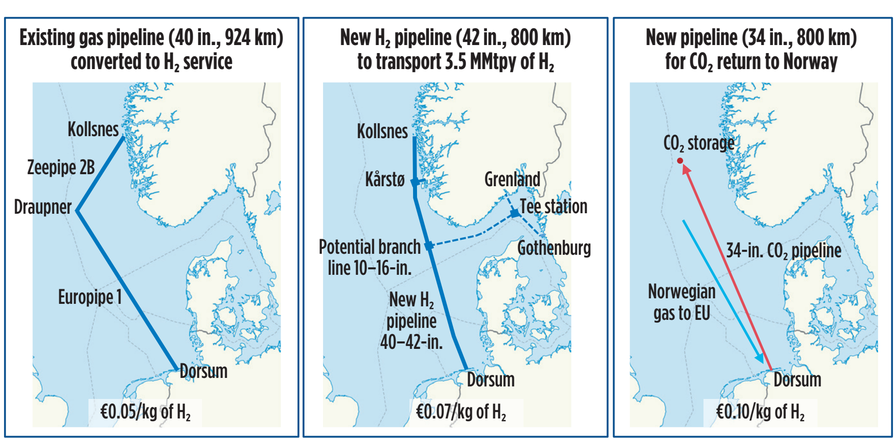

FIG. 4. Example costs of gas pipelines for efficient H_2 transportation.

transportation of H_2 might be an option for these areas.

The major markets for blue H_2 solutions with long-distance pipelines are Europe, the U.S., Canada, Australia, the Middle East, Japan, South Korea and, to an extent, Southeast Asia. Some countries, like China, prefer to use coal as a source for H_2 production. In principle, this is a viable option since coal is cheap, but the CO_2 emissions volume to be handled is about twice as great as for natural gas. Furthermore, the cleanup prior to gas reforming is extensive.

Based on 2020 reports[1,2] by the International Energy Agency and Concawe, the author's company has estimated the major users of blue H_2 solutions. The main market segments for blue H_2 include:

- Direct use, ammonia and e-fuel
- Biofuel production
- H_2 for carbon capture, storage and utilization in industry.

Considering the uncertainties and sustainability issues connected to e-fuel and biomass, the estimates indicate a need for the startup of a world-scale blue H_2 plant every two weeks, globally, from 2030. A world-scale blue H_2 plant would produce approximately 400,000 tpy of H_2. The need for CO_2 storage would be 8 t–10 t of CO_2/t of H_2.

Reduction of CO_2 emissions. Emissions-free blue H_2 may be used to efficiently produce clean fuels or to cut CO_2 emissions from power generation, buildings and industry, as shown in **FIG. 5.**

Blue H_2 may also be a competitive pre-combustion alternative to post-combustion carbon capture from flue gas (exhaust). By replacing natural gas with low-cost, emissions-free blue H_2 in industrial processes, very competitive CO_2 abatement costs may be realized. Also, the total CO_2 emitted will be less due to the high cost of capturing the last fractions of CO_2 from flue gas with the use of amine, etc. (10%–20%).

LITERATURE CITED

1 International Energy Agency, "Energy technology perspectives," September 2020.

2 A. Soler, under supervision of M. Yugo, "Role of e-fuels in the European transport system—Literature review," Concawe Low Carbon Pathways Joint Group and Concawe Fuels and Emissions Management Group, January 2020, Online: https://www.concawe.eu/wp-content/uploads/Rpt_19-14.pdf

TORKILD R. REINERTSEN is Chairman and Market Lead for Hydrogen at REINERTSEN New Energy AS in Trondheim, Norway. Dr. Reinertsen has been delivering engineering and EPC projects to oil and gas companies for 30 yr. At REINERTSEN New Energy, he focuses on solutions and technologies for clean and efficient H_2 production with carbon capture and storage. He also specializes in complete value chains for H_2, H_2 carriers and clean fuels. Additionally, Dr. Reinertsen is the Founder of HYDROGEN Mem-Tech, which has developed efficient palladium membrane technology for the separation of H_2 from gas mixtures.

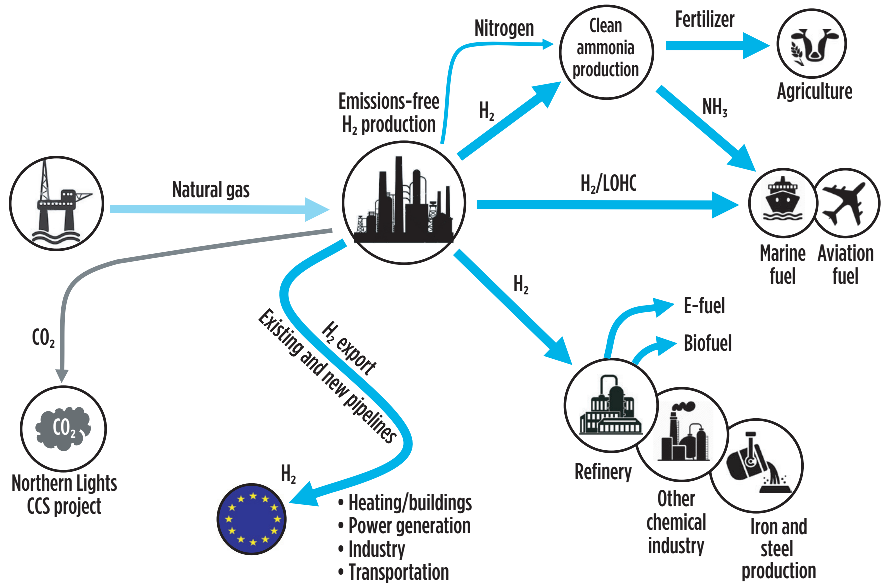

FIG. 5. H_2 value chains.

Increasing blue hydrogen production affordability

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Large-scale, affordable, "blue" hydrogen production from natural gas, along with carbon capture, utilization and storage (CCUS), is necessary to bridge the gap until large-scale H_2 production using renewable energy becomes economic. The cost of carbon dioxide (CO_2) already makes blue H_2 via steam methane reforming (SMR) competitive against gray H_2 (without CCUS), and a newly available process[a] based on gas partial oxidation (POX) technology and pre-combustion CO_2 capture solvent technology further increases the affordability of blue H_2 for greenfield projects.

Why blue H_2? A growing number of national governments and energy companies, including Shell,[1] have announced net-zero-emission ambitions. Although renewable electricity is expanding rapidly, without low-carbon H_2 as a clean-burning, long-term-storable, energy-dense fuel, a net-zero goal is difficult to achieve, especially when it comes to decarbonizing fertilizer production and hard-to-abate heavy industries such as steel manufacturing and power generation. H_2 also has potential as a transport and heating fuel that could repurpose existing gas distribution infrastructure or be introduced into existing natural gas supplies.

Consequently, H_2 plays an important part in many green strategies. The EU's H_2 strategy,[2] published in July 2020, describes it as "…essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution."

Momentum is building with a succession of commitments to H_2 by various companies and governments. For example, in June 2020, Germany announced a €9-B H_2 strategy,[3] and the International Energy Agency stated, "Now is the time to scale up technologies and bring down costs to allow hydrogen to become widely used."[4] Over the past 3 yr, the number of companies with membership in the international Hydrogen Council—which predicts a tenfold increase in H_2 demand by 2050[5]—has jumped from 13 to 81 and includes oil and gas companies, automobile manufacturers, trading companies and banks.

In 2018, global H_2 production was 70 MMtpy.[4] Today's demand is split between use for upgrading refined hydrocarbon products and as a feedstock for ammonia production for nitrogen fertilizers. Nearly all H_2 production comes from fossil fuels: it accounts for 6% of natural gas and 2% of coal consumption, as well as 830 MMtpy of CO_2 emissions[6]—more than double the UK's emissions.[7] Gray H_2 is a major source of CO_2 emissions. If H_2 is to contribute to carbon neutrality, it must be produced on a much larger scale and with far lower emissions levels.

Over the long term, the answer is likely to be "green" H_2, which is produced from the electrolysis of water powered by renewable energy. This supports the integration of renewable electricity generation by decoupling production from use. H_2 becomes a convertible currency enabling electrical energy to be stored and used as an emissions-free fuel and chemical feedstock.

Green H_2 projects are starting. For example, a Shell-led consortium is at the feasibility stage of the NorthH2 wind-to-H_2 project in the North Sea, and a Shell–Eneco consortium secured the right to build the 759-MW Hollandse Kust Noord project at a subsidy-free Dutch offshore wind auction in July 2020; this project will include a green H_2 technology demonstration.

However, electrolysis alone will not meet the forecast demand. It is expensive at present, and there is insufficient renewable energy available to support large-scale green H_2 production. To put the scale of the task into perspective, meeting today's H_2 demand through electrolysis would require 3,600 TWh of electricity, more than the EU's annual use.[4] Moreover, using the current EU electricity mix would produce gray H_2 from electrolysis with 2.2 times the greenhouse gas emissions of producing gray H_2 from natural gas.[8] This is because nearly half (45.5%) of the net electricity generated in the EU comes from burning natural gas, coal and oil,[9] and generating electricity from natural gas, for example, has a 44% efficiency.[10]

An alternative is blue H_2 produced from natural gas, coupled with CCUS. H_2 production via electrolysis has a similar efficiency to blue H_2 production, but the levelized cost of production is significantly higher for electrolysis at €66/MWh, compared with €47/MWh for SMR–CCUS.[11]

In addition, it is widely acknowledged that scaling up blue H_2 production will be easier than delivering green H_2. For example, the EU strategy[2] states, "Other forms of low-carbon hydrogen [i.e., blue] are needed, primarily to rapidly reduce emissions … and support the parallel and future uptake of renewable [green] hydrogen."

However, the strategy goes on to claim that neither green nor blue H_2 production is cost-competitive against gray; the H_2 costs estimated for the EU are €1.5/kg for gray, €2/kg for blue and up to €5.5/kg for green.[4] These costs are based on an assumed natural gas price for the EU of €22/MWh, an electricity price of €35/MWh–€87/MWh and a capacity cost of €600/kW.

With the cost of CO_2 at \$25/t–\$35/t, blue H_2 becomes competitive against gray even with higher capital costs, and green H_2 still may be more than double the price of blue H_2 by 2030 (**FIG. 1**).[4] Some forecasts indicate that cost parity will occur around 2045.[12]

This competitiveness between blue and gray H_2 (when considering CO_2 costs) is based on SMR technology, but other technologies are available to further increase blue H_2 affordability for greenfield projects.

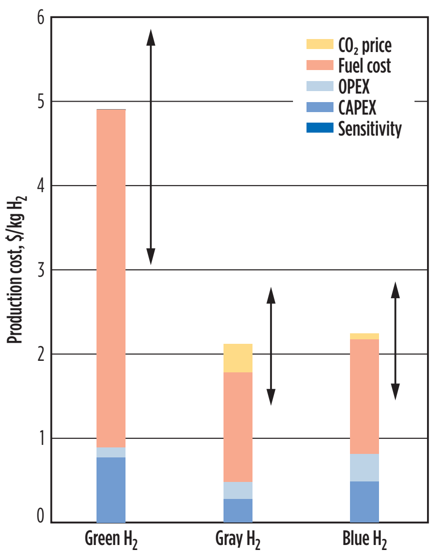

FIG. 1. Estimated H_2 production costs in 2030.

Greenfield technology options. This article considers three technology options for greenfield blue H_2 projects: SMR, autothermal reforming (ATR) and a proprietary gas POX technology[b] (**FIG. 2**).

SMR. SMR, a proven catalytic technology widely applied for gray H_2 production, uses steam in a multi-tubular reactor with external firing for indirect heating. More than 48% of H_2 production is from natural gas, with SMR being the most common production technology.[13] Post-combustion carbon capture[c] can be retrofitted to convert gray H_2 production to blue and is proven to capture nearly all the CO_2 (99%) from low-pressure, post-combustion flue gas.

However, for greenfield blue H_2 applications, oxygen (O_2)-based systems, such as ATR and gas POX technology, are more cost-effective than SMR (**FIG. 3**), a conclusion backed by numerous studies and reports.[14] **Note:** The cost of CO_2 makes gray H_2 via SMR more expensive than blue H_2 from SGP technology. The cost advantage of O_2-based systems over SMR increases with scale because the relative cost of the air separation unit decreases with increasing capacity. Another advantage is that more than 99.9% of the CO_2 can be captured using the lower-cost, pre-combustion solvent technology.[d]

ATR. ATR uses O_2 and steam with direct firing in a refractory-lined reactor with a catalyst bed. It is more cost-effective than SMR, but it requires a substantial feed gas pre-treatment investment, and the fired heater produces CO_2 emissions (**FIG. 2**). ATR can be combined with pre-combustion carbon-capture technology to convert gray H_2 production to blue.

Gas POX technology. Gas POX technology is also an O_2-based system with direct firing in a refractory-lined reactor, but it is a noncatalytic process that does not consume steam and has no direct CO_2 emissions. It, too, can be combined with pre-combustion carbon-capture technology for blue H_2 production. Compared with SMR, gas POX technology saves money by maximizing the carbon-capture efficiency and simplifying the process lineup, both of which offset the cost of O_2 production (**FIG. 4**).

POX vs. ATR for blue H_2. As O_2-based systems offer clear benefits over SMR, this article considers the advantages of the proprietary gas POX technology[b] over ATR for blue H_2 production.

A key advantage is that the POX reaction does not require steam as a reactant. Instead, high-pressure steam is generated by using waste heat from the reaction, which can satisfy the steam consumption within the blue H_2 process, as well as some internal power consumers.

With no need for feed gas pre-treatment, gas POX technology has a far simpler process lineup than ATR (**FIG. 2**). Also, as a noncatalytic, direct-fired system, it is robust against feed contaminants such as sulfur and can accommodate a large range of natural gas qualities, thereby giving refiners greater feed flexibility to decarbonize refinery fuel gas.

Gas POX technology[b] provides substantial savings compared with ATR—a 22% lower levelized cost of H_2 (**FIG. 5**). These savings come from a 17% lower CAPEX owing to the potential for a higher operating pressure leading to a smaller H_2 compressor (single-stage compression), CO_2 capture and CO_2 compressor

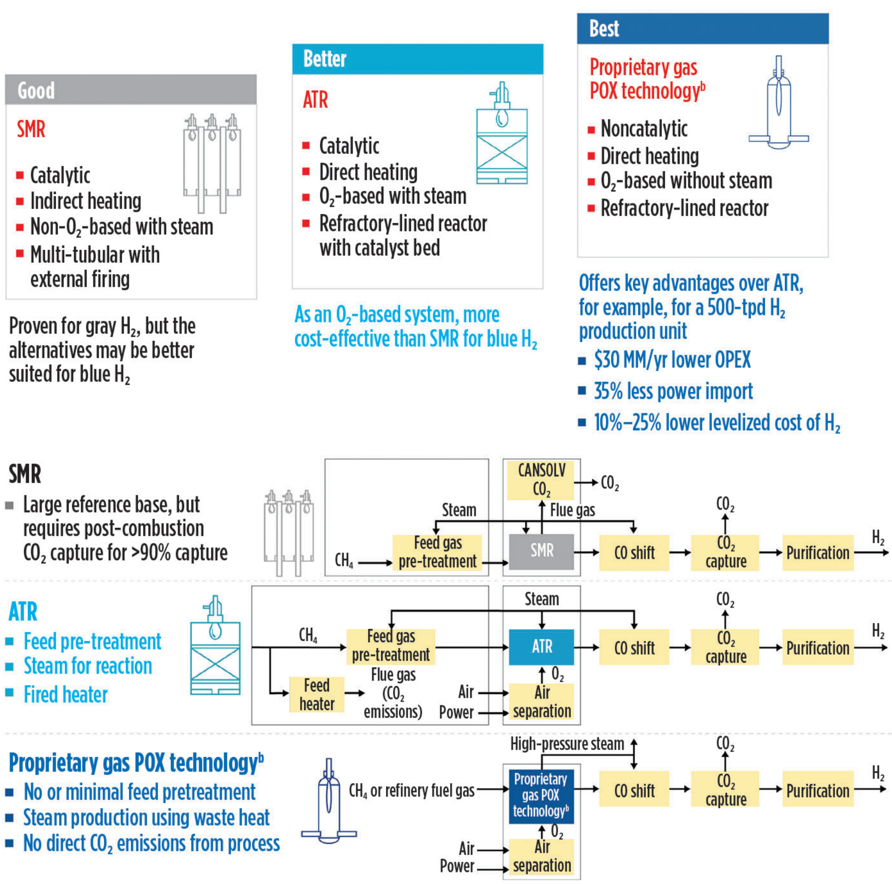

FIG. 2. Blue H_2 technologies and process lineups.

units, and a 34% lower OPEX (excluding the natural gas feedstock price) from reduced compression duties and more steam generation for internal power. Gas POX technology consumes 6% more natural gas, but this is offset by power generation from the excess steam.

The proprietary blue H_2 process[a] is an end-to-end lineup that maximizes the integration of the gas POX and solvent technologies. Compared with an ATR unit, modeling shows (based on the parameters in **TABLE 1**) that a lineup producing 500 tpd of pure H_2 would have:

- \$30 MM/yr lower OPEX
- 35% less power import
- > 99% CO_2 capture
- 10%–25% lower levelized cost of H_2.

The gas POX–solvent process is the best option for large-scale blue H_2 projects. **FIG. 6** shows the principle advantages of integrating it with other proprietary and open-source technologies.

The choice between a methanator or a pressure-swing absorption (PSA) unit for the H_2 purification step depends on the required H_2 purity. For example, a PSA unit is necessary to achieve the > 99.97% purity required for the H_2 used in fuel cells. The offgas is predominantly H_2, with trace containments such as CO, CO_2 and nitrogen. In the ATR process, this offgas is typically burned to preheat the natural gas, which produces direct CO_2 emissions.

In a methanator, the purity of the final H_2 is lower (> 98%, depending on the feed gas properties). However, it avoids the direct CO_2 emissions from burning the PSA offgas. The main advantage of choosing a methanator is that H_2 is not lost via the PSA offgas. Consequently, it reduces natural gas consumption for the same H_2 production. In addition, a methanator is commonly applied in industry, as it satisfies the H_2 purity requirements of most industrial consumers.

History of gas POX oxidation technology. Gas POX technology[b] is mature and "low-carbon," which makes it eligible for government funding. It has a long history of development and usage. For example, research into oil gasification was being conducted in Amsterdam, the Netherlands as early as 1956.

Today, the proprietary gas POX technology[b] has more than 30 active residue and gas gasification licensees, and more than 100 gasifiers using the technology

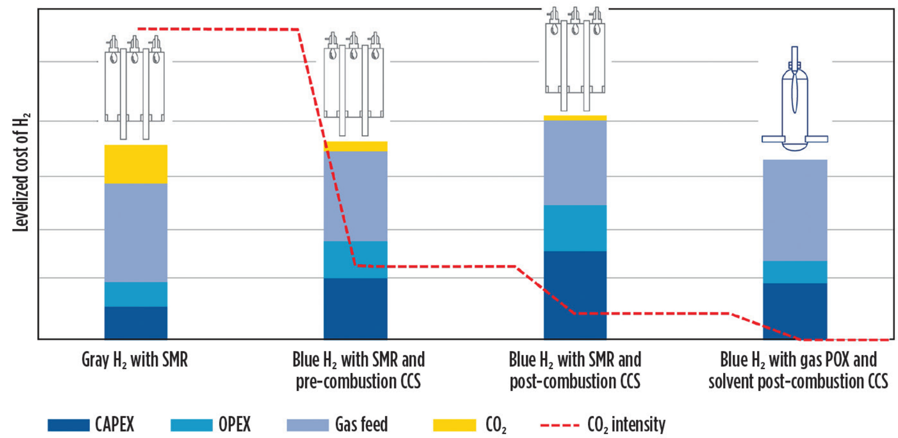

FIG. 3. Relative CO_2 intensity and cost of gray and blue H_2 via SMR with pre- and post-combustion capture, and blue H_2 via proprietary gas POX[a] and pre-combustion capture solvent[d] technologies.

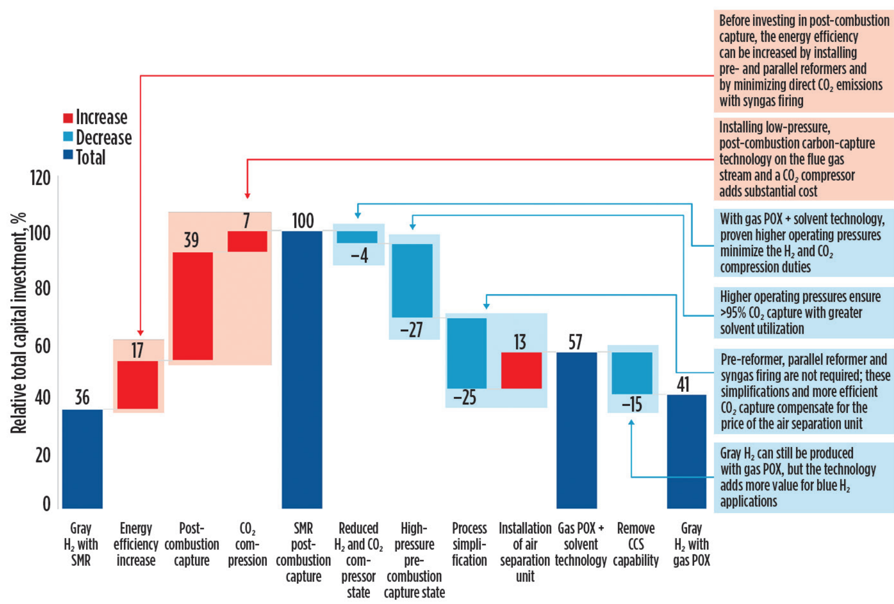

FIG. 4. Relative capital investment comparison between gray and blue H_2 via SMR and gas POX technology.

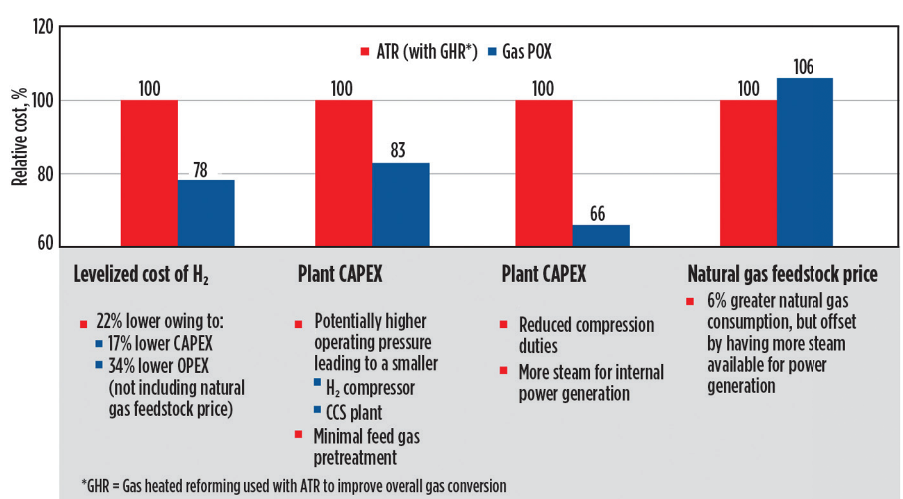

FIG. 5. The cost of gas POX technology relative to ATR.

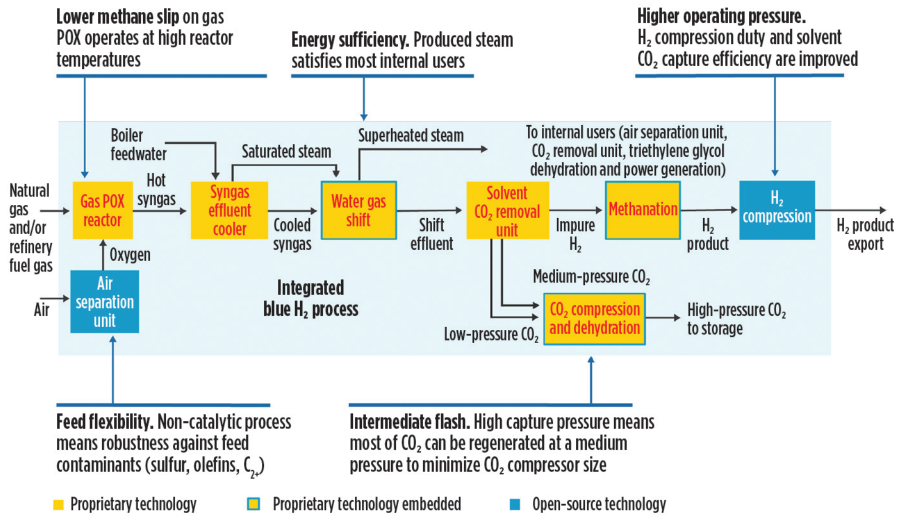

FIG. 6. The advantages of integrating the proprietary blue H_2 process with other technologies, with Shell as the master licensor.

TABLE 1. Modeling parameters

Pure H_2 production, tpd*	500
Natural gas cost, $/t equivalent	396
Demineralized water, $/t equivalent	8.4
Power import, $/MWh	86
H_2 discharge pressure, bara	72
CO_2 discharge pressure, bara	150
Plant availability, %	95

*Excluding inerts, methane, CO_2 and CO, which will also be present, depending on the final purification step. Solvent, triethylene glycol and catalyst costs are estimated.

have been built worldwide. For example, the Pearl gas-to-liquids (GTL) plant in Qatar has 18 trains, each with an equivalent pure H_2 production capacity of 500 tpd. Pearl GTL has been operating since 2011. The product is defined as pure H_2 production—i.e., not including any inerts, methane, CO_2 or CO, which will also be present, depending on the final purification step.

Since 1997, the Pernis refinery in the Netherlands has been operating a 1-MMtpy carbon-capture program using the technology. The CO_2 is used in local greenhouses. The CO_2 stream is an essential part of the Pernis CCS project.

No matter how cost-effective the H_2 production and carbon-capture technologies, without sequestering the CO_2 directly or through enhanced oil recovery, the H_2 remains gray. Many CCUS projects are in operation at various stages throughout the world. For example, since 2015, the Shell Quest facility in Canada has captured and stored more than 5 MMt of CO_2.

Key takeaways. H_2 will be part of the future energy mix, and several mature technologies are available for producing cost-effective, low-carbon blue H_2. For greenfield applications, SMR is an inefficient method of producing blue H_2 owing to poor CO_2 recovery and scalability; O_2-based systems offer better value (an independently backed conclusion).

The proprietary blue H_2 process,[a] which integrates proprietary gas POX[b] and solvent[c] technologies, offers key advantages over ATR, including a 10%–25% lower levelized cost of H_2, a 20% lower CAPEX, a 35% lower OPEX (excluding natural gas feedstock price), > 99% CO_2 captured and overall process simplicity. The process, which is now available to third-party refiners, is proven at the 500-tpd scale.

NOTES

[a] Refers to the Shell Blue Hydrogen Process (SBHP)
[b] Refers to the Shell gas partial oxidation process (SGP)
[c] Refers to the Shell CANSOLV CO_2 Capture System (CANSOLV is a Shell trademark)
[d] Refers to Shell ADIP ULTRA solvent technology

LITERATURE CITED

[1] Van Beurden, B., "A net zero emissions energy business," Shell, April 16, 2020, Online: https://www.shell.com/media/speeches-and-articles/2020/a-net-zero-emissions-energy-business.html
[2] European Commission, "A hydrogen strategy for a climate-neutral Europe," July 7, 2020, Brussels, Belgium.
[3] Press and Information Office of the German Federal Government, "German government adopts hydrogen strategy," June 10, 2020, Online: https://www.bundesregierung.de/breg-en/news/wasserstoffstrategie-kabinett-1758982
[4] International Energy Agency, "The future of hydrogen," June 2019.
[5] Hydrogen Council, "Hydrogen scaling up: A sustainable pathway for the global energy transition," November 13, 2017, Online: https://hydrogencouncil.com/en/study-hydrogen-scaling-up/
[6] International Energy Agency, "Hydrogen," 2021, Online: https://www.iea.org/fuels-and-technologies/hydrogen
[7] EU Science Hub, 2018, Online: https://ec.europa.eu/jrc/en
[8] Adolf, J. *et. al,* "Shell hydrogen study: Energy of the future? Sustainable mobility through fuel cells and hydrogen," January 2017.
[9] Europa, Eurostat, "Electricity production, consumption and market overview (based on 2018 data)," June 2020, Online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview#Electricity_generation
[10] U.S. Energy Information Administration, "Table 8.1: Average operating heat rate for selected energy sources," (Assuming a heat rate of 7,800 Btu/kWh for natural gas power plants), Online: https://www.eia.gov/electricity/annual/html/epa_08_01.html
[11] Pöyry Management Consulting, "Hydrogen from natural gas—The key to deep decarbonisation," July 2019, Online: https://www.poyry.com/sites/default/files/zukunft_erdgas_key_to_deep_decarbonisation_0.pdf
[12] European Zero Emission Technology and Innovation Platform, "Commercial scale feasibility of clean hydrogen," April 25, 2017, Online: https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-Commercial-Scale-Feasibility-of-Clean-Hydrogen-report-25-April-2017-FINAL.pdf
[13] International Renewable Energy Agency (IRENA), "Hydrogen from renewable power: Technology outlook for the energy transition," September 2018, Online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf
[14] IEA Greenhouse Gas R&D Programme (IEAGHG), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS," IEAGHG Technical Review 2017-TR3, 2017, Online: https://ieaghg.org/publications/technical-reports/reports-list/10-technical-reviews/778-2017-tr3-reference-data-supporting-literature-reviews-for-smr-based-hydrogen-production-with-ccs

NAN LIU is the Licensing Technology Manager for Gasification at Shell Catalysts & Technologies. She has fulfilled roles throughout the project lifecycle, from initial feasibility and front-end development to project execution and plant operations, on major capital projects around the globe. These projects include the startup of the gasification unit at the Fujian refinery and ethylene project in China, as well as performance optimization at the gasification and hydrogen plant at Shell's Pernis refinery in the Netherlands. Ms. Liu has a strong commercial mindset and is a keen advocate of gasification as a value-adding investment.

Metallurgical damage mechanisms affecting equipment in the ammonia industry

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Considerable investment has been allotted to the research and development of renewable and alternative forms of energy in the private sector, in academia and by governments around the world. The impetus for the recent interest in these energy forms is to provide an alternative to fossil fuels by deploying new technology that enables these alternative and renewable forms of energy to address climate change. Examples of these types of technology include battery energy storage systems; electrochemical fuel cells; and even new and novel types of batteries, including graphene and lithium metal batteries.[1,2] These technologies are at different stages of development and vary from commercially available to theoretical research.

Technology utilizing hydrogen fuel has been successfully implemented as an alternative energy source globally.[3] H_2 fuel cells have been available in commercial form in vehicles and in power generation applications for decades. New electrochemical fuel cells utilizing ammonia fuel are a promising new technology alternative to direct H_2 and hydrocarbon fuel cells. Recent interest in ammonia anode fuel cells has sparked investment in this technology as a potential replacement for petroleum-powered vehicles and power generation.[4] Ammonia also provides promise, as it may provide a source of H_2 fuel for H_2 technology. However, accommodating increased usage of ammonia anode and even H_2 fuel cells using ammonia as the H_2 source requires significant increases in ammonia production capacity globally.

Creating large-scale infrastructure for ammonia and H_2 fuels requires an objective assessment of the associated operational and lifecycle risks. It is important to recognize that consideration of all potential hazards and threats throughout the supply chain is a multidisciplinary undertaking to ensure successful deployment and safe operation of the supply chain. On the production side of the supply chain, ammonia process equipment is susceptible to hazards and threats in the form of materials degradation and metallurgical damage mechanisms from the process fluids handled by ammonia production and handling equipment.

This article highlights three common metallurgical damage mechanisms that can result in potentially dangerous equipment failures and costly downtime in ammonia process equipment if not properly managed. Additionally, this article discusses methods to identify and diagnose these damage mechanisms, susceptible materials, inspection methods for identifying damage, and mitigation options and important points of consideration for operating and maintaining such equipment. The goal is to connect various parts of the ammonia production process and process variables with how they may influence the damage mechanisms of the production equipment discussed in this article.

Description of the ammonia process.

It is important to discuss the steps and units in the ammonia production process. For the synthesis of ammonia, a carbon/H_2 source, water and nitrogen are fed into the front end of the plant to provide a feed stream of fresh syngas: H_2 and nitrogen in an approximate ratio of 3:1.

Normally, the feed stream to ammonia synthesis (the back end) is free of CO and CO_2, and may contain small amounts of water and inerts such as methane and argon. In a cryogenic purifier process, the final front-end steps remove impurities that make the methanation and molecular sieve/NH_3 washing steps unnecessary.

FIG. 1 shows the units in the ammonia process, with the top row indicating the front-end units and the bottom row showing the back-end units.

Ammonia equipment materials of construction.

Most equipment in the ammonia production process are essentially pressure vessels and piping leading to storage tanks with pressure boundaries constructed of metallic materials. All materials of construction used in the ammonia industry are susceptible to degradation and various types of damage mechanisms. While it may be possible to select materials of construction that are completely resistant to attack by the process fluids, such an approach is often impractical.

Carbon and low-alloy steels are the most commonly used materials of construction for process equipment in the ammonia industry. These materials offer a suitable combination of strength and ductility, and are capable of safely operating in the temperature ranges often seen in the ammonia industry. However, carbon and low-alloy steels are susceptible to corrosion damage mechanisms.

Stainless steel alloys and nickel-based alloys, depending on the types selected, provide resistance to corrosion attack in

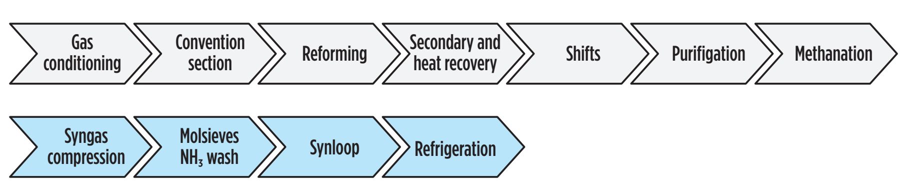

FIG. 1. Typical ammonia production process flow diagram.

environments containing carbonic, acid and chlorides. However, these materials are not impervious to corrosion.

Copper alloys are highly susceptible to corrosion attack in ammonia environments and should be avoided for equipment in the pressure boundary or in direct contact with process fluids in the ammonia industry.

Three metallurgical damage mechanisms commonly affect ammonia equipment and are discussed in relation to process variables, process equipment and materials of construction:

- High-temperature hydrogen attack (HTHA)
- Environmentally assisted stress corrosion cracking (SCC)
- Brittle fracture.

Awareness of mechanisms that can damage equipment is essential in developing solutions to properly inspect the equipment, mitigate damage and prevent failure. The pertinent damage mechanisms are also input for evaluations regarding fitness-for-service as the mechanism and rate of attack need to be understood to determine the remaining life. For a proper risk-based inspection (RBI) program or during a hazards analysis, the appropriate mechanisms are identified so that the probability of failure can be determined in addressing reliability issues.[5]

High-temperature H_2 attack (HTHA). HTHA is a form of degradation caused by H_2 reacting with carbon to form methane in a high-temperature environment. When steel is exposed to H_2 at elevated temperatures, H_2 will diffuse into the alloy and combine with carbon to form small pockets of methane. The methane is trapped at grain boundaries and in voids and does not diffuse out of the metal. Once accumulated, the methane expands, forming voids that can lead to initiated cracks in the steel. An example of such fractures, viewed in the microstructure of a carbon steel pipe weld, is shown in **FIG. 2.**[6] High-strength, low-alloy steels are particularly susceptible to this mechanism, which leads to embrittlement of the bulk parent metal. The embrittlement in the material can result in a catastrophic brittle fracture of the asset.[7–10]

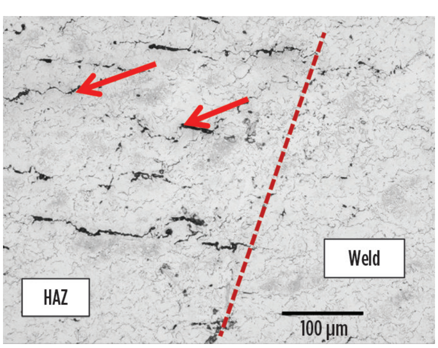

FIG. 2. H_2 damage observed in the carbon steel line at the heat-affected zone (HAZ). Decarburization and fissuring region caused by H_2 depleting the iron carbides. Nital etch. (Original magnification: 200 times).[6,12]

Susceptible materials include high-strength, low-alloy steels (legacy C–½Mo steels), plain carbon steels, non-post-weld heat-treated (PWHT) welds, and copper alloys. Alloy steels such as 1.25Cr–0.5Mo provide resistance for milder HTHA conditions, but the alloy must be matched properly to the process conditions that the metal sees. API RP 941 provides guidance to aid in materials selection for fixed equipment operating in environments with H_2 partial pressures at elevated temperatures and pressures.[11] This guidance also can be useful to materials engineers and process engineers alike, as knowledge of both process conditions and the materials of construction will provide information on an asset's susceptibility to this particular damage mechanism.

The most obvious equipment concerns are any equipment exceeding normal operating temperatures or operating window limits, specifically carbon and low-alloy steel vessels and piping operating at temperatures that are above the API RP 941 Nelson curve values. Aging plants should be mindful of API RP 941 Nelson curve changes and should determine whether process changes or HTHA mitigation strategies may be implemented. HTHA is not a concern in stainless steel vessels; however, stainless steel-lined vessels with the possibility of high H_2 partial pressure behind the liner are a concern.

H_2 content is high in the ammonia process streams—up to 67% on a volume basis—and it is important to evaluate for HTHA potential where the temperatures rise above 204°C (400°F) for carbon steel materials. The H_2 content should be considered on a wet gas basis, which may reduce the risk susceptibility for equipment prior to condensation of water vapor occurring after the shift unit.

Typical concerns start with the shift unit and equipment through the ammonia synthesis loop, where temperatures are above 204°C (400°F). However, HTHA may be present in other areas, such as secondary unit pressure shells due to refractory failure, which can lead to high temperatures on steel pressure shells. Referring to **FIG. 1,** HTHA also can be a concern throughout the ammonia process, including equipment in the shift units (both high and low shift), methanation and synthesis loop.

Synthesis loop equipment, particularly converters without furnace stress relief or operating at high temperatures on the pressure shells, and startup heater coils are also vulnerable points for attack. Additionally, hot spots from refractory failures can occur in the primary reformer outlet, in secondary reformer and waste heat boilers, molsieves and pressure envelopes. Thermal imaging inspections or other means are used to monitor hotspots on refractory lined pressure shells of HTHA (or creep) in susceptible materials.

Hester and Benac provide details regarding an investigation conducted into a carbon steel effluent cooler header piping rupture, installed in an ammonia converter and synthesis loop, that occurred 5 yr after a change in operating conditions. The process temperature was increased from 232°C (450°F) to 510°C (490°F), and the operating pressure was decreased from 29 MPa (4,200 psig) [14.5 MPa (2,100 psig) H_2 partial pressure] to 23.4 MPa (3,400 psig) [11.7 MPa (1,700 psig) H_2 partial pressure]. This process change placed the carbon steel pipe above the API RP 941 Nelson curve temperature for carbon steel at the corresponding H_2 partial pressure. The piping rupture was found to have a brittle fracture appearance.

Failure analysis revealed that HTHA was the damage mechanism that caused the pipe rupture. This example case demonstrates the vulnerability of this portion of the ammonia process if material limits are exceeded and how process changes can create the potential for eventual failure.[6,12] Uncontrolled materials substitutions can also lead to failures.

Several inspection methods may be successfully used to identify HTHA:

- Visual inspection
- Advanced ultrasonic backscattering techniques (AUBT)
- Advanced phase array
- High-sensitivity wet fluorescent magnetic particle testing (WFMT)

- Time of flight diffraction (TOFD)
- Replication of surfaces
- Positive material identification (PMI)
- Thermographic temperature surveys.

Note: These methods are highly dependent on the technique and skill level of the inspector. False positives and negatives are possible with improper techniques and inadequate skill levels. This is why it is essential to consult qualified inspection experts to assist in inspection efforts.

One of the most critical ways to mitigate the potential for HTHA is for plant engineering to review plant processes, U1 materials of construction and operating conditions to identify potential HTHA risks with H_2-containing equipment. An important component of this includes conducting an engineering review of pressure, H_2 partial pressure and temperature. Operating with safety margins—e.g., 10°C (50°F) below the API RP 941 Nelson curve—also can provide additional assurance. Engineering should establish integrity operating limits for all vulnerable equipment. Materials control programs are essential, including guards against uncontrolled materials substitutions, and active positive materials identification programs for incoming materials and field/retro components.

If feasible, aging plants should consider reviewing potential replacement of equipment with higher-alloy material that is less susceptible to HTHA, according to the API RP 941 Nelson curve for desired operating conditions. This review should include determining whether welded equipment or piping was post-weld heat-treated, and if not known, assume non-post-weld heat-treated and operate at lower temperature and pressure. Installing temperature indicators at critical locations to monitor actual temperatures and performing regular thermography measurements can help ensure that operating windows and limits are not exceeded, or identify those that need to be addressed.

Environmentally assisted stress corrosion cracking (SCC). SCC occurs when a susceptible material is exposed to a specific environment and tensile stress. The combination of these three factors leads to brittle fracture of normally ductile materials at stress levels within the normal operating range. Multiple types of environmentally assisted SCC exist, including chloride SCC, amine SCC and ammonia SCC.

Nitrate SCC may come from exposure to nearby nitric acid, ammonium nitrate, or urea emissions that hydrolyze to form nitrate. During stress corrosion cracking, the material may not show signs of wall loss or pitting, but fine cracks will form within the material or on the surface. This process has serious implications on the utility of the material because the applicable safe stress levels are drastically reduced in the corrosive medium. Some environments of concern are potash, nitrates and sulfides.[7,13,14,15]

The most common cracking mechanism detected in ammonia storage tanks, spheres and other process equipment is ammonia SCC (NH_3 SCC), which is a function of ammonia exposure in conjunction with an O_2 source—typically O_2 or CO_2. NH_3 SCC can occur at atmospheric liquid ammonia conditions of –33°C (–27°F), but at faster rates at higher temperatures under pressurized ammonia conditions. Tanks used for transporting liquid NH_3, like rail tank cars, tank cars, barges and vessels, are also susceptible to SCC.

For ammonia equipment, susceptible materials to NH_3 SCC include carbon steel, low-alloy steels and stainless steels exposed to high O_2 levels or chlorides. Residual stress within parts increases the potential for SCC; therefore, post-weld heat treatment (PWHT) of carbon steels can lower the probability of SCC. PWHT is often used to mitigate NH_3 SCC in pressurized equipment. NH_3 storage tanks are also particularly susceptible to NH_3 SCC, as they may lack PWHT and be more susceptible to O_2 contamination in the presence of NH_3. High hardness can be a concern, as higher hardness material is more susceptible, with the heat-affected zone (HAZ) and areas with localized stress being the most vulnerable. Vapor spaces may be preferentially attacked due to higher temperatures and the higher presence of O_2 that is not protected by water in the NH_3 liquid phase.

For NH_3 equipment, chlorides may be present in insulation or cooling waters, both of which can result in SCC of stainless steels. Affected NH_3 process units include susceptible materials in the convection unit, such as headers exposed to chlorides in insulation; primary reformer inlet pigtails; the synthetic loop startup heater coils, which may be exposed to atmospheric SCC promoters; and exchangers with seawater or cooling water with high chloride content.

Several inspection methods can be used to identify SCC cracks:

- Wet fluorescent magnetic particle testing (WFMT)
- Angled beam ultrasonic (UT) at weld HAZs
- Hydrostatic testing
- Acoustic emissions testing (AET)

NH_3 SCC is mitigated by avoiding air, O_2 and CO_2 sources, and by the addition of small amounts of water (0.2%) where O_2 may be present. The design and operation of atmospheric tanks should avoid vacuum conditions that would pull air into the vapor space. Vapor spaces are more susceptible due to higher temperatures and the higher presence of O_2 that is not protected by water in the ammonia. Especially where PWHT is not practical, such as atmospheric storage tanks, materials are specified with both minimum and maximum hardness, and suitable weld materials are chosen. For chloride SCC, keeping steam temperatures below 60°C (140°F) can prevent cracking in stainless steel heat exchangers.

Brittle fracture. The loss of ductility determines whether a brittle fracture could occur. The conditions, mechanisms and/or degradations that cause the loss of ductility must be considered. Brittle fracture occurs when a material breaks with little to no plastic deformation. Typically, a fracture occurs rapidly, with no warning and with less energy needed than a ductile fracture. **FIG. 3** shows a brittle fracture that occurred suddenly in an NH_3 plant.[17,18]

Most metals undergo a ductile-to-brittle transition in fracture toughness with decreasing temperature. Carbon steel and low-alloy steel materials will undergo a transformation from ductile-to-brittle behavior as the material tem-

FIG. 3. Brittle fracture of a pressure vessel in an ammonia plant.

perature drops, resulting in low toughness at low temperatures and increasing the hazard of brittle fracture. Increasing the thickness of a material can result in higher ductile-to-brittle fracture temperatures. A typical impact energy curve, or Charpy curve, is shown in **FIG. 4.**[8,16]

Brittle fracture can occur in the presence of a small flaw in a low-toughness material when stresses are sufficiently high. It is a concern in NH_3 equipment since NH_3's boiling point of –34°C (–29°F) is slightly less than the common carbon steel minimum design metal temperature (MDMT) of –29°C (–20°F). Refrigerated services typically require material specifications and/or Charpy impact testing to avoid introducing brittle fracture hazards to the plant.

A limited portion of the NH_3 process sees these temperatures in normal conditions. NH_3 process units where brittle fracture is a concern include the synthesis loop, syngas compression, refrigeration, molsieves, NH_3 wash and cryogenic purification. Equipment such as chillers, flash drums and NH_3 product separators may be susceptible to reaching temperatures below the ductile brittle transition temperature (DBTT) for steels. Depressurization will lower temperatures, and repressurization controls may be needed to ensure that the stresses are acceptable. In older plants, refrigeration chillers may not meet existing guidelines, or they may be operated at lower-than-DBTT temperatures.

NH_3 in refrigeration service or in cryogenic storage systems typically operate in a cold condition. NH_3's saturation temperature at atmospheric pressure is –34°C (–29°F). There are, however, a number of instances and situations where brittle fracture failures are a concern in the NH_3 industry. The use of carbon or low-alloy steel, thick-walled loop equipment is likely to have increased MDMT. Auto-refrigeration can reduce temperatures below the MDMT.[16,17,18]

Pressure vessels using steels pre-1987 materials of construction and older equipment produced prior to ASME code revisions recognizing plane strain impacts on DBTT can be more susceptible to brittle fracture.[19] Use of inferior, vintage-grade steels such as SA212, SA285 and SA225—which are prone to brittle fracture under certain conditions—are more vulnerable. Carbon steels and low-alloy steels with low toughness and an existing flaw or crack, and materials that contain residual stresses due to improper stress relief or that do not undergo PWHT, are more susceptible. Normalized steel is less susceptible to brittle fracture than steels having undergone other treatment.

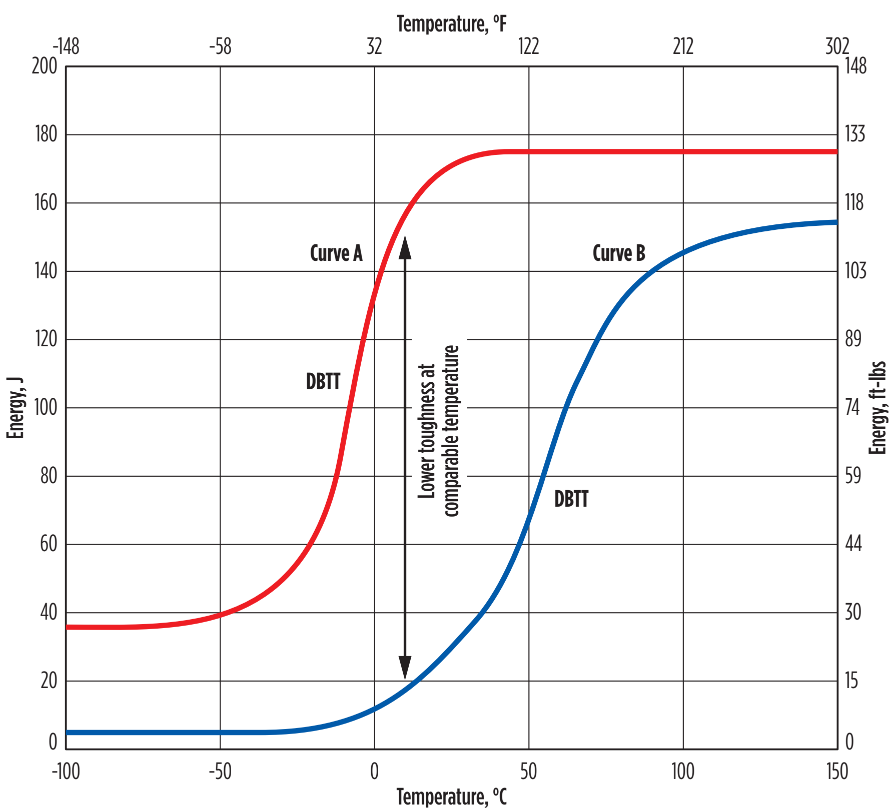

FIG. 4. Charpy impact curves showing the transition from a ductile behavior to a more brittle behavior as the temperature decreases.[17]

Operationally and from a design standpoint, pressurized ammonia systems that normally operate above –29°C (–20°F) can quickly decrease in temperature below the minimum allowable when the system is depressurized. Additionally, thicker wall vessels created for high pressure, such as those found in the syngas compression, synthesis loop and purge units, are more susceptible. These vessels can have significantly higher minimum design temperatures for the same materials due to plane strain, and are more likely to fall below their minimum allowable temperatures at ambient conditions. Liquid nitrogen exposures (including nitrogen purge equipment and process equipment under poor purge controls) are a hazard, and liquid nitrogen supply contractors may introduce a brittle fracture hazard to the site if using improper equipment.

To prevent brittle fracture, inspection methods should focus on the initiation of cracks. After initiation, ensure that the crack size is stable to avoid fast and unstable fracture. Methods using API 579-1/ASME Fitness for Service, Part 9 and other specifications can be used for this assessment.[20,21] Typical inspection methods to search for cracks include:

- Ultrasonic testing (UT) for cracks, particularly in welds
- Penetrant testing (PT)
- Magnetic particle testing (MT)

Options to mitigate brittle fracture include following up-to-date ASME codes for carbon steel pressure vessel materials that are subject to temperatures of less than –29°C (–20°F). Selecting proper materials for equipment and piping based on establishing the appropriate MDMT, including the use of fine-grained carbon steels with proven toughness by impact testing, nickel-containing low-alloy steels with 9% Ni steel at temperatures as low as –196°C (–320°F), austenitic stainless steels (i.e., 300 series), and aluminum alloys (because they have no ductile-to-brittle transition when cooled), are essential to preventing brittle fracture.

Performing PWHT to relieve stress can be used to improve the DBTT of the equipment. Using good welding procedures and filler metals to avoid porosity and lack of fusion are helpful, as well. Performing a cold embrittlement fracture assessment, as outlined in API 579-1/ASME Fitness for Service FFS-1, Part 3, or completing a fracture mechanics assessment per API 579-1/ASME Fitness for Service FFS-1, Part 9 for cracks found during inspection can help mitigate brittle fracture.

Finally, for operators and process engineers, use of operating procedures and temperature controls to keep equipment above the DBTT when pressurized are critical to preventing brittle fracture.

Recommendations. Hydrogen technology is expected to play a particularly important role in the future of renewable and alternative forms of energy. Ammonia technology and the NH_3 process are expected to see substantial growth to accommodate existing technologies, as well as new technology currently in development. With the growth and expansion of the ammonia cycle and the creation of new facilities to increase production, ensuring safe operation and mitigating hazards is essential.

Safe equipment design, operation and maintenance of NH_3 equipment and assets is a collaborative effort between ammonia process engineers, mechanical design and asset integrity engineers and materials engineers. For mechanical and materials engineers, it is important to have a collaborative understanding of the ammonia process parameters—e.g., operating pressures, temperatures, chemical compositions of process fluids, etc., to make informed materials selection decisions. For the process engineer, it is important to have a general understanding of how decisions to change process parameters during a revamp to improve efficiency, for example, may impact the assets of a particular material of construction.

Implementation of the right programs and bringing in knowledgeable technical experts with experience in the hazards and threats within this industry are essential to ensuring that accurate assessments are completed and that safety, longevity and proper mitigation of hazards are guaranteed. To this end, the authors' consultancy created a joint industry program (JIP) with numerous participants that are operators in the ammonia industry. The 2020–2021 JIP focuses on improving safety and reliability in the ammonia and fertilizer industry. The first year of the JIP included the identification of damage mechanisms and mitigation options for plant equipment in the ammonia process. The overall plan for the JIP provides for subsequent-year studies that will address other safety and reliability issues, including damage mechanisms and mitigation options for other fertilizer industry processes including urea, nitric acid and ammonium nitrate.[22]

LITERATURE CITED

1. Koohi-Fayegh, S. and M. A. Rosen, "A review of energy storage types, applications and recent developments," *Journal of Energy Storage,* Vol. 27, February 2020.
2. Kim, H., H. D. Lim, J. Kima and K. Kang, "Graphene for advanced Li/S and Li/air batteries," *Journal of Materials Chemistry A,* Iss. 1, 2014.
3. Abe, J. O., A. P. I. Popoola, E. Ajenifuja and O. M. Popoola, "Hydrogen energy, economy and storage: Review and recommendation," *International Journal of Hydrogen Energy,* Vol. 44, Iss. 29, June 7, 2019.
4. Lim, D. K., A. B. Plymill, H. Paik, X. Qian, S. Zecevic, C. R. I. Chisholm and S. M. Haile, "Solid acid electrochemical cell for the production of hydrogen from ammonia," *Joule 4,* November 18, 2020.
5. Baker, J., D. J. Benac and D. Shaffer, "Damage mechanism reviews and mitigation methodology for ammonia equipment," Safety in Ammonia Plants and Related Facilities Symposium, 2019.
6. Benac, D. J. and M. W. Hester, "Elevated temperature failure mechanisms in ammonia plant equipment—Reducing the risk of failure" Safety in Ammonia Plants and Related Facilities Symposium, 2013.
7. American Petroleum Institute (API), API 571, Sec. 3.36, "Damage mechanisms affecting fixed equipment in the refining industry," 3rd Ed., March 2020.
8. Urzendowski, M. and D. Chronister, "Unexpected cases of HTHA in gasoline desulfurization units," API Equipment and Standards Meeting, May 2011.
9. Chemical Safety Board (CSB) Bulletin 2005-04-B, "Positive material verification: Prevent errors during alloy steel systems maintenance," October 2006.
10. Prueter, P. E., R. Jones, J. Hess and J. DeLuca, "Managing the risks associated with a hydrotreater reactor with possible high-temperature hydrogen attack," Proceedings of the ASME 2019 Pressure Vessels and Piping Division Conference, San Antonio, Texas, July 14–19, 2019.
11. API Recommended Practice 941, "Steels for hydrogen service at elevated temperatures and pressures in petroleum refineries and petrochemical plants" 8th Ed., 2016.
12. Hester, M. W. and D. J. Benac, "Reducing the risk of HTHA failures," *World Fertilizer Magazine,* October 2019.
13. Loginow, W., "Stress corrosion cracking of steel in liquefied ammonia service—A recapitulation," National Board of Pressure Vessel Inspectors, National Board Bulletin, January 1989.
14. Russell, A. M., "Testing and recommended practices to improve nurse tank safety," Phase 1, U.S. Department of Transportation, FMCSA-RRR-13-032, October 2013.
15. "Stainless steels in ammonia production," Committee of Stainless Steel Producers, AISI, November 1978.
16. Macejko, B., "Is your plant vulnerable to a brittle fracture?" *Hydrocarbon Processing,* November 2014.
17. Benac, D. J., D. Shaffer and D. Wood, "Managing cold temperature and brittle fracture hazards in ammonia-related industries," Safety in the Ammonia Plants and Facilities Symposium, 2015.
18. Benac, D. J., N. Cherolis and D. Wood, "Managing cold temperature and brittle fracture hazards for pressure vessels," *Journal of Failure Analysis and Prevention,* February 2016, Vol. 16.
19. American Society of Mechanical Engineers, "Boiler and Pressure Vessel Code, Section 8: Rules for Construction of Pressure Vessels, Division 1," New York, New York, 2017.
20. API 579-1/ASME Fitness for Service FFS-1: "Assessment of existing equipment for brittle fracture," Part 3, June 2016.
21. British Standard Institute, BS7910, "Guide on methods for assessing the acceptability of flaws in metallic structures," December 2019.
22. Baker, J., D. J. Benac and D. Shaffer, "Ammonia and fertilizer industry joint industry program—A resource to manage damage mechanisms and mitigation options," *World Fertilizer,* 2020.

SEAN BERG works in BakerRisk's San Antonio, Texas office as part of the Investigation and Materials Group. He has a background in both mechanical engineering and metallurgical and materials engineering, and is a registered professional engineer practicing in both disciplines. As a university professor, he has taught university coursework and conducted research in each of these areas of engineering. With 10 yr of experience as an engineer, Dr. Berg has expertise in structural and mechanical integrity of fixed and rotating equipment, fitness-for-service assessments, failure analysis of plant and refinery equipment, high-pressure high-temperature (HPHT) drilling and production systems, and forensic investigation of property damage and determining origin and cause of losses resulting from fire, water, weather and external forces. Dr. Berg is also a specialist in batteries and battery materials, with in-depth expertise in battery energy storage systems and associated hazards.

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DOROTHY SHAFFER is a subject matter resource for ammonia-related production and terminal facilities. She has 20 yr with a major ammonia producer in production, process engineering, project engineering and as Director of Risk and Reliability, and 15 yr of consulting work on mechanical integrity programs, process safety and risk evaluation work. Mrs. Shaffer's background bridges gaps among process, operations and mechanical integrity programs in ammonia-related fields.

SHOW PREVIEW

A. BLUME, Editor-in-Chief

H2TECH SOLUTIONS
H2-TECHSOLUTIONS.COM | MAY 18-19, 2021

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- Attendance is FREE
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H2Tech Solutions, a virtual technical conference from *H2Tech,* will bring together engineers, technologists and managers working to advance fuel, chemical and industrial applications for hydrogen.

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H2Tech Solutions is hosted by Gulf Energy Information and *H2Tech,* and sponsored by Chart Industries, Cummins, Haldor Topsoe, Nel Hydrogen and Siemens Energy. Supporting organizations include Fuel Cells and Hydrogen Joint Undertaking, Gas Infrastructure Europe, GPA Europe, Dii Desert Energy/MENA Hydrogen Alliance, Fuel Cell & Hydrogen Energy Association, Green Hydrogen Coalition, and Renewable Hydrogen Alliance.

For questions about sponsorships at H2Tech Solutions, please contact Melissa.Smith@GulfEnergyInfo.com. For questions about the H2Tech Solutions agenda, please contact Adrienne.Blume@H2-Tech.com. We look forward to seeing you (virtually) there!

SPEAKERS FROM:

Blue Hydrogen Production	Green Hydrogen Production	Technology Pathways to Decarbonization	Integration of Green H_2 in Infrastructure
Shell, Linde, Evonik, Honeywell UOP, Johnson Matthey	ITM Power, Evonik, Sener, ABB	Air Liquide, fuelcellenergy	thyssenkrupp, NewFortress energy

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GLOBAL PROJECTS DATA

A. BLUME, Editor-in-Chief

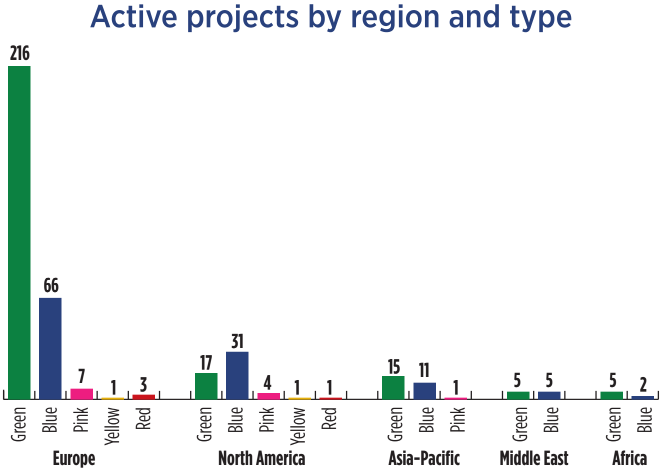
Gulf Energy Information's Global Energy Infrastructure (GEI) Database and Construction Boxscore Database are tracking 381 active and operating carbon-neutral and low-carbon H_2 production and utilization projects around the world.

Among green, blue, pink, yellow and red H_2 production projects that will produce and/or use H_2 as a carbon-free, climate-friendly energy carrier, the vast majority—around 77%—are located in Europe. Breakdowns of active and operating project market share and project numbers by region and H_2 production type are shown below.

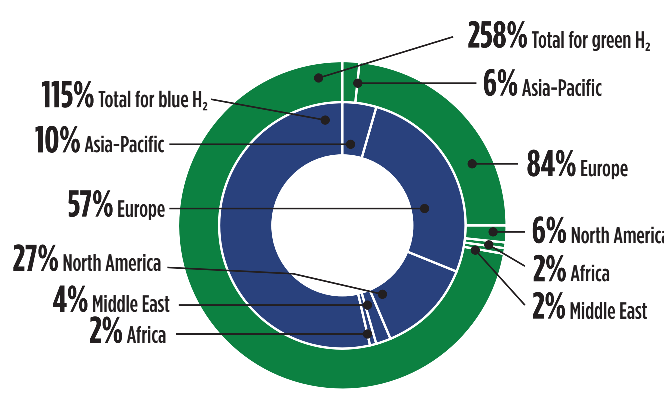
The map at right, provided by GEI's Energy Web Atlas, shows the distribution of active and operating H_2 projects of various types throughout Asia-Pacific. As shown on the map, green H_2 projects are multiplying rapidly in Australia, and H_2 for transportation applications are prominent in both Australia and Japan. China is the world's largest producer of gray H_2, although blue and green H_2 production projects are gaining footholds in the country's industry. For more information on active low-carbon H_2 projects in Asia-Pacific, please see this issue's Regional Report.

Active and operating H_2 projects in Asia-Pacific

Active projects by region and type



Active project market share by region, green and blue H_2



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HYDROGEN COLOR LEGEND BY *H2TECH*

Feedstock type	H_2 production type	Production technology	Power source/ feedstock	Emissions	Notes
Renewable	Green	Water electrolysis	Renewable electricity	None	Also referred to as clean H_2 or carbon-neutral H_2
	Pink	Water electrolysis	Nuclear power	None	
	Red	Biomass gasification	Forestry and agricultural crops and residues, animal residues, municipal solid waste	Low CO_2 emissions	Heat, steam and O_2 inputs are used to convert biomass to H_2 in a non-combustion process
	Olive	Algal or bacterial photosynthesis (via bioreactor)	Green microalgae or cyanobacteria provide enzymatic pathways; water and sunlight provide power	None	Holds promise for future large-scale, eco-friendly H_2 production
Renewable/ non-renewable	Yellow	Water electrolysis	Mixed-origin grid energy	Low CO_2 emissions	Electricity source can be a mix of renewable power and fossil fuels
Non-renewable	Blue	Methane reforming + CCUS* Gasification + CCUS	Natural gas Coal	Low CO_2 emissions	Also referred to as low-carbon H_2
	Turquoise	Methane pyrolysis	Natural gas	Solid carbon byproduct	
	Gray	Methane reforming	Natural gas	Medium CO_2 emissions	Accounts for 70% of present H_2 production
	Brown	Coal gasification	Lignite coal	High CO_2 emissions	Highly polluting
	Black	Coal gasification	Bituminous coal	High CO_2 emissions	
	White/ Clear	Generated by raising the temperature of oil reservoirs, or naturally occurring	Few viable exploitation strategies exist	Low/no CO_2 emissions	One technology injects O_2 into spent oilfields to generate H_2 and extract it using a downhole filter

*Carbon capture, utilization and storage (CCUS)

EVENTS CALENDAR

A. BLUME, Editor-in-Chief

The H_2 Events Calendar keeps readers updated on hydrogen sector and related industry events that are accessible by the industry public. These events may be virtual and/or live, and are hosted by industry associations and trade organizations, governmental organizations and companies.

Please visit the websites and contacts below for more information on these events, and please email Editors@H2-Tech.com to alert our editorial team of upcoming industry events.

MAY

H2Tech Solutions
May 18–19
Virtual event
www.H2-TechSolutions.com
(See box for contact information)

Energy Storage World Forum
May 19–20, Virtual event
www.energystorageforum.com
E: emily@energystorageforum.com
P: +44 203-097-1833

Regional Hydrogen Energy Conference
May 24
Optaija, Croatia
www.hydrogeneurope.eu/index.php/events/rhec-1st-regional-hydrogen-energy-conference
E: ankica.kovac@fsb.hr
P: +385 1-616-8218

JUNE

AIChE's Center for Hydrogen Safety Asia-Pacific Conference
June 1–3
Virtual Event
www.aiche.org/chs/conferences/center-hydrogen-safety-asia-pacific-conference/2021
E: chs@aiche.org
P: 800-242-4363 / +1 203-702-7660

InnovationsForum Mobility
June 8–9
GDI Gottlieb Duttweiler Institute, Rüschlikon, Switzerland
www.innovationsforum-mobility.ch
E: annabell@lhi.ag
P: +41 71-544-6960

International Hydrogen Symposium
June 14–15
Chamber of Commerce Hamburg, Hamburg, Germany
www.h2symposium.de
E: info@ihk-nord.de
P: +49 40-3613-8385

Hydrogen & P2X: Fuel Cells, Road Transport and Energy Production
June 16–17
Copenhagen, Denmark
www.fortesmedia.com/hydrogen-p2x-2021,4,en,2,1,4.html
E: events@fortesmedia.com
P: +48 61-250-4880

World Hydrogen Technologies Convention co-located with **f-cell + HFC**
June 20–24, Virtual event
www.whtc2021.org
E: natalie.vollbrecht@messe-sauber.de
P: +49 711-656-960-5708

ZEROEMISSION 2021 with **H2 Hydrogen & Fuel Cells 2021**
June 23–24
Piacenza Expo, Piacenza, Italy
www.zeroemission.show
E: events@zeroemission.show
P: +39 26-630-6866

European Fuel Cell Forum 2021
June 29
Culture and Convention Centre, Lucerne, Switzerland and Virtual Event
www.efcf.com/2021
E: forum@efcf.com

JULY

Vienna Energy Forum
July 6–7
Hofburg Imperial Palace, Vienna, Austria
www.viennaenergyforum.org
E: vef@unido.org

Connecting Green Hydrogen APAC 2021 Conference and Exhibition
July 19–20
Pullman Melbourne Albert Park, Melbourne, Australia
www.greenhydrogenevents.com
E: amy@leader-associates.com
P: +86 21-3417-3967

ees Europe with **Power2Drive Europe** and **Green Hydrogen Conference and Exhibition**
July 21–23
Messe München, Munich, Germany
www.ees-europe.com/conference
E: krucker@conexio.expert
P: +49 72-31-5859-8186

World Renewable Energy Congress
July 26–30
Instituto Superior Técnico, Lisbon, Portugal
www.wrec2020.tecnico.ulisboa.pt
E: manuel.guedes@tecnico.ulisboa.pt
P: +351 96-773-2478

AUGUST 2021

International Conference & Exhibition on Clean Energy
Aug. 9–11
Courtyard by Marriott Ottawa Downtown, Ottowa, Canada
icce2020.iaemm.com
E: ICCE2020@iaemm.com
P: 613-830-1760

SEPTEMBER

International Hydrogen Aviation Conference (IHAC 2021)
Sept. 2
DoubleTree by Hilton Strathclyde, Glasgow, Scotland
www.hy-hybrid.com/ihac-2021
E: info@hy-hybrid.com
P: +44 0-74-2431-2756

CCSHFC 2021: Hydrogen and Fuel Cells—The Time Is Now
Sept. 7
National Exhibition Center, Birmingham, UK
www.climate-change-solutions.co.uk
E: jacqui.staunton@climate-change-solutions.co.uk
P: 07-86-655-2833

Gastech Hydrogen
Sept. 13–16
Singapore Expo, Singapore
www.gastechevent.com/gastech-hydrogen
E: info@dmgevents.com
P: +971-4-438-0355 / +65 6856-5205 / +44 203-615-5902

f-cell Stuttgart
Sept. 14–15
Haus der Wirtschaft, Stuttgart, Germany
www.f-cell.de
E: natalie.vollbrecht@messe-sauber.de
P: +49 711-656-960-5708

2021 International Hydrogen Conference
Sept. 12–15
Jackson Lake Lodge, Moran, Wyoming
www.conferences.illinois.edu/hydrogen
E: mmarqua2@illinois.edu
P: +1 217-244-8174

Electric & Hybrid Marine World Expo Virtual Live
Sept. 13–15
Virtual Event
www.electricandhybridmarinevirtuallive.com
E: oliver.taylor@ukimediaevents.com
P: +44 1306-74-3744

Hydrogen+Fuel Cells International at SPI 2021
Sept. 20–23
Ernest N. Morial Convention Center, New Orleans, Louisiana and Virtual Event
www.solarpowerinternational.com/hydrogen
E: spi@xpressreg.net
P: 800-748-4736 / +1 508-743-8522

International Conference on Hydrogen Safety
Sept. 21–23
McEwan Hall, University of Edinburgh, Edinburgh, Scotland
www.ichs2021.com
E: ichs@hysafe.org

International Hydrogen & Fuel Cell Expo
Sept. 29–Oct. 1
Tokyo Big Sight, Tokyo, Japan
www.fcexpo.jp/en-gb.html
E: visitor-eng@wsew.reedexpo.co.jp
P: +81 3-3349-8576

OCTOBER

World Hydrogen Conference
Oct. 4–6
Amsterdam, the Netherlands
www.worldhydrogencongress.com
E: oliver.sawyer@greenpowerglobal.com
P: +44 20-7099-0600

Hydrogen Online Conference
Oct. 7–8
Virtual event (24 hr)
www.hydrogen-online-conference.com
E: silke.frank@mission-hydrogen.de
P: +49 71-95-904-3900

NOTE: Due to the COVID-19 pandemic, industry event dates are constantly changing, while others are being postponed or canceled. Please consult the appropriate association or organization to confirm event dates, locations and details.

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