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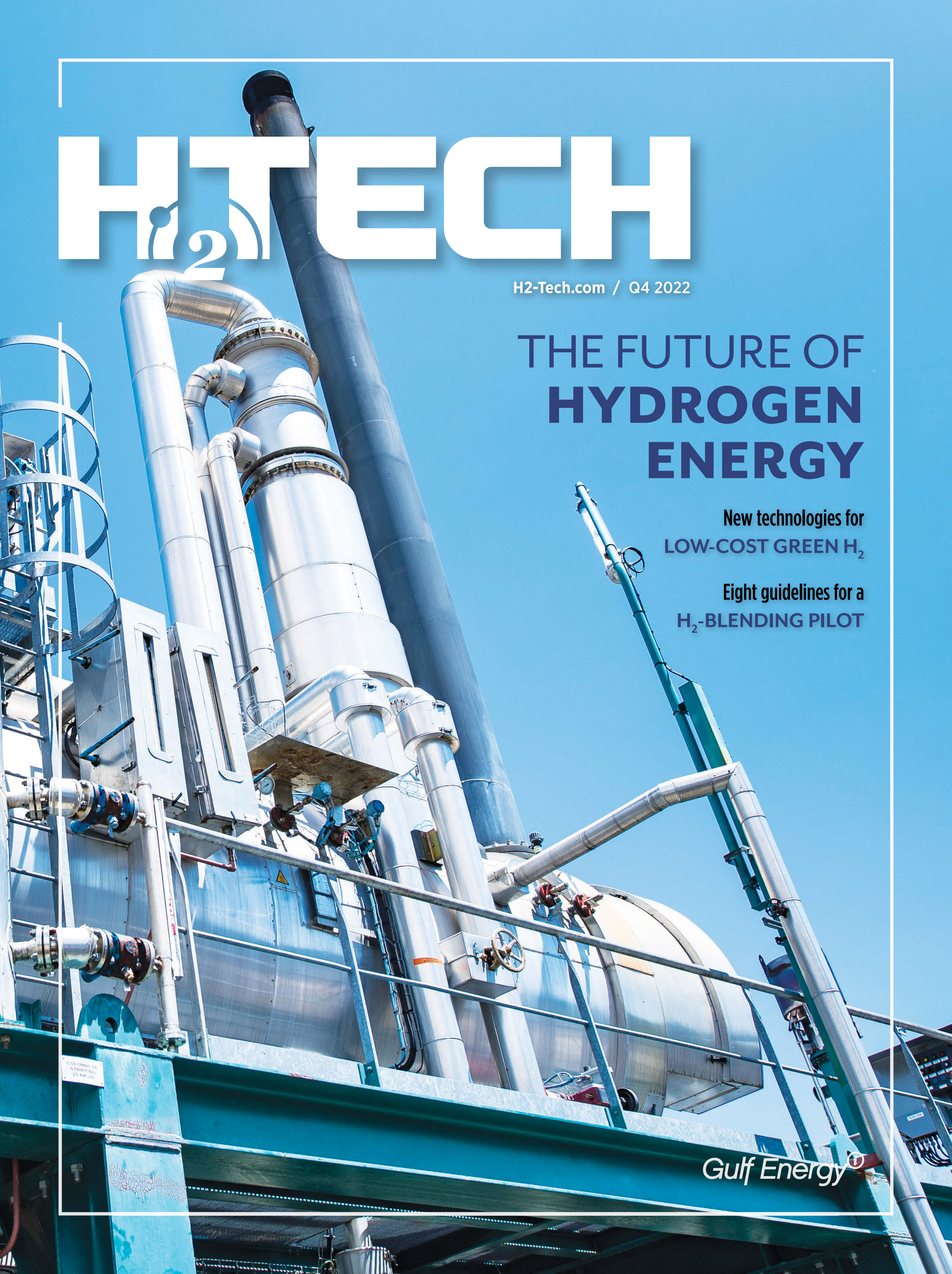
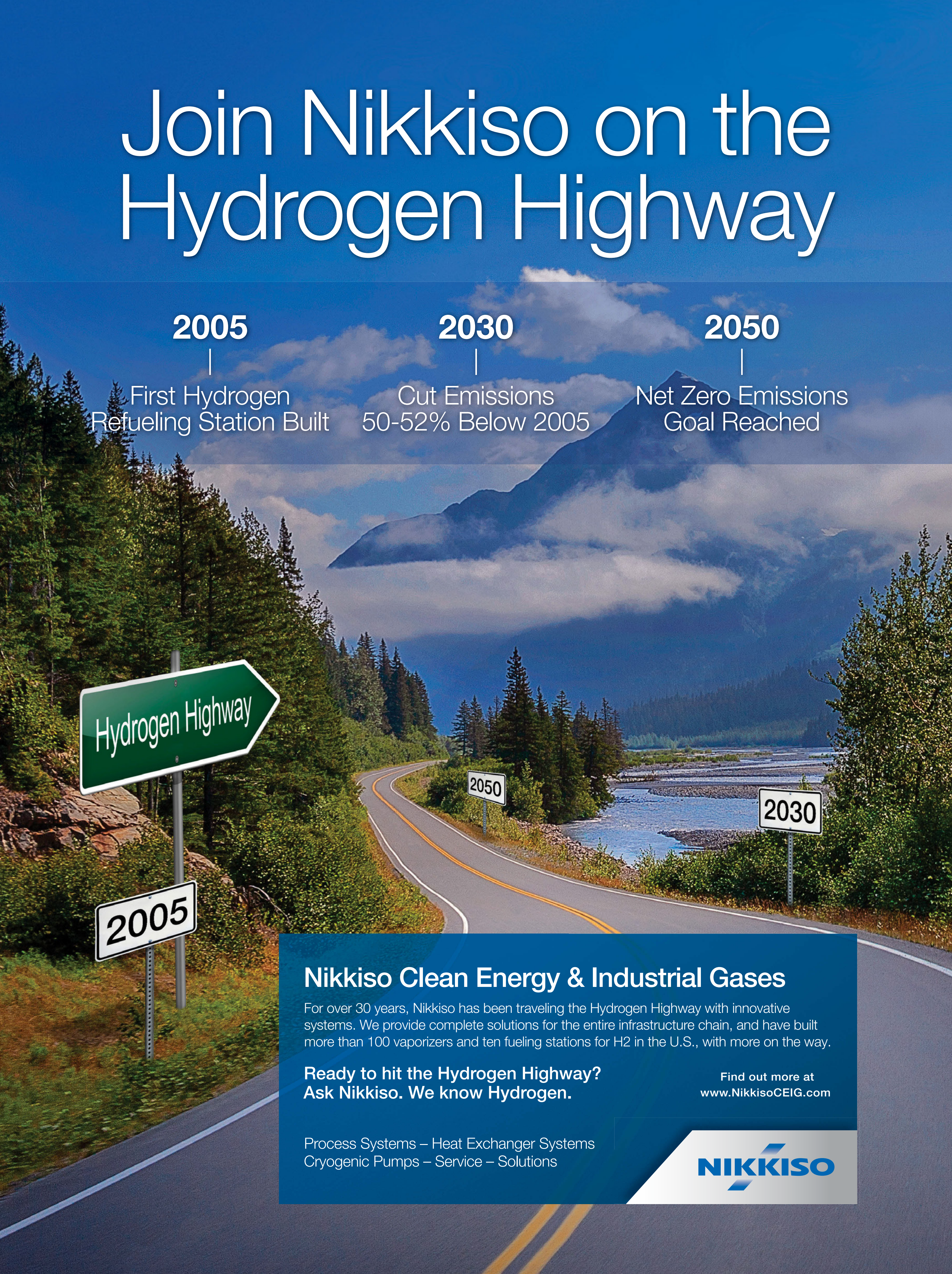
THE FUTURE OF HYDROGEN ENERGY

New technologies for LOW-COST GREEN H_2

Eight guidelines for a H_2-BLENDING PILOT



Gulf Energy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Cover Image: View of ENGIE's gas storage infrastructure. Photo courtesy of ENGIE.

EDITORIAL COMMENT

Developing electrolyzer technology is a key component for the future of H_2 energy

TYLER CAMPBELL,
Managing Editor

On August 22, 2022, U.S. President Joe Biden signed the Inflation Reduction Act. This legislation boasts $369 B in climate and clean energy investments with a focus on clean H_2, and it offers a clean H_2 tax credit for H_2 projects and storage technologies. The act is the most ambitious climate-focused legislation ever passed by the U.S. Congress.

According to Gulf Energy Information's Global Energy Infrastructure database, 100 of the more than 700 H_2 projects in either the planning stage or under construction are in the U.S. These projects are mainly in Texas, Louisiana and California, with the majority being green and blue H_2 projects. The blue H_2 projects, which use carbon capture and storage, will be eligible for a tax credit, with additional tax incentives offered to facilities that utilize the captured carbon.

The future of H_2 energy. There is still much improvement needed to completely integrate H_2 into the global energy mix and meet global climate goals of net-zero emissions by 2050. To accomplish these ambitious initiatives, 2030 will be the first milestone. According to the International Energy Agency's (IEA's) *Hydrogen Supply Report,* in 2021, low-emissions H_2 production was approximately 0.6 MMt.[1] For the 2050 targets to be reached, low-emissions H_2 production must be increased to 95 MMt by 2030.

Low-emissions H_2 production technology must be rapidly progressed to reach this milestone. Electrolysis is a promising method to produce green H_2, but each type of electrolyzer is in different stages of advancement.

According to the IEA, proton exchange membrane and alkaline electrolyzers are at the market uptake level, solid oxide electrolyzer cells are still under demonstration, and anion exchange and anion exchange membrane electrolyzers are still at the prototype level (**FIG. 1**). However, these technologies are not yet competitive with gray H_2 production technologies. Developing green H_2 production technologies will be essential to the future of H_2 energy.

LITERATURE CITED

[1] International Energy Agency, Hydrogen Supply, 2022, online: "https://www.iea.org/reports/hydrogen-supply

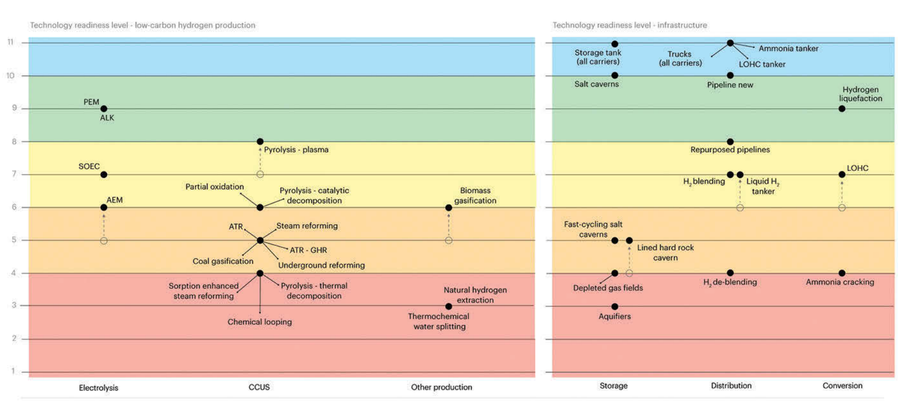

FIG. 1. Technology readiness for level–low carbon H_2 production and infrastructure.
Source: International Energy Agency.

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Enhancing how we deliver technical knowledge: The evolution of *H2Tech*

For the past several years, *H2Tech* has provided the global hydrogen value chain with the latest advancements in processing technologies, maintenance, safety and know-how to improve and enhance blue and green hydrogen production, electrolyzers, the latest in hydrogen infrastructure and distribution, transportation and much more. The publication has been instrumental in disseminating ideas across the globe that have ultimately made the hydrogen industry safer and more efficient, sustainable and profitable.

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In addition, our advertising and sponsorship partners expect *H2Tech* to lead by example and deliver a superior return on investment. With all that in mind, I am excited to announce that starting with our January 2023 issue, we will deliver all content through digital platforms.

This natural evolution of the way we deliver information, industry trends and technology advancements to our global readership will provide our readers an enhanced pathway to the latest topics industry professionals are seeking.

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As the hydrogen industry continues to evolve, so will the way we deliver the latest advancements in hydrogen production and the technologies that propel this industry forward. We are excited to embark on this new chapter for *H2Tech*. We are also thrilled about what the future holds and are here to assist you in any way.

Kind regards,

LEE NICHOLS

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INFRASTRUCTURE AND DISTRIBUTION

A feasibility study: Decarbonization through H_2 fuel

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The author's company's decarbonization initiatives have been implemented to reduce carbon emissions and achieve future net-zero aspirations. This aligns with Saudi Arabia's Green Initiative to cut domestic carbon output through a carbon circular economy roadmap by 2060.

One method explored was decarbonizing domestic gas networks by replacing natural gas with hydrogen (H_2) to reduce emissions from industrial natural gas networks. This is achievable by creating a blended stream within the existing gas network. The addition of H_2 decreases the carbon content, resulting in reduced carbon dioxide (CO_2) emissions when used as a combustion fuel at the end user's facility. Upstream blue or green H_2 production methods must be employed to gain the decarbonization benefits of H_2-blended gas.

As a result, a feasibility study was performed to evaluate methods of H_2 blending. This study presented multiple options at various cost levels, leading to varying degrees of decarbonization benefits.

The assessment focused on the existing gas network—every gas network is unique in terms of the design limitation and type of end users silicification. As shown in **FIG. 1,** several workstreams were evaluated and summarized in **TABLE 1.**

The study provided two options: blending H_2 directly into the grid, and blending H_2 at the end user's battery limit by supplying H_2 through a dedicated pipeline.

Blending H_2 directly into the grid was studied based on various components, which included process, pipelines, custody meters, field instrumentation, gas turbines, compressors, fired heaters, boilers and valves. Seven cases were studied covering a range of injection percentages for H_2 to assess the impact on the network.

All components showed an acceptance limit of up to 5%–10%, except pipelines that showed a lower limit due to high-grade materials operating at high pressure. The same challenge has been encountered elsewhere in the oil and gas industry when operating a high-pressure natural gas network. It is

TABLE 1. Assessment of existing gas networks

No.	Workstream
WS1	Process
WS 2A	Custody meters
WS 2B	Field instruments
WS 3	Pipelines
WS 4A	Fired heaters and boilers
WS 4B	Gas turbines and compressors
WS 4C	Valves

TABLE 2. The H_2 blending limits for the various components

Workstream	Study's findings
Process	The study showed up to 10% H_2 limitation due to the minimum of 930 Btu/sft^3 of higher heating value specifications of the blended sales gas received by end users.
Custody meters	Components are expected to handle up to 10% H_2 without major modifications. Some gas chromatograph changes and software updates may be required for flow and supervisory computers.
Field instruments	All field instrumentation is expected to handle up to 10% H_2 without requiring changes. Above this limit, some instrumentation may need to be replaced.
Pipelines	Uncertainty on the threshold blending limit at high pressure is subject to research, with further testing results expected to be published in literature, JIPs and industry codes.
Fired heaters	Can handle more than 10% H_2 without requiring any major modifications.
Boilers	Can handle more than 10% H_2 without requiring any major modifications.
Gas turbines	Blending up to 5% H_2 is expected to be a low-cost impact scenario, and turbines are restricted to a maximum 30% blending limit due to technological constraints.
Compressors	Blending up to 9% H_2 for a variable-speed compressor is expected to maintain performance at a low added cost. Fixed-speed machines will experience a significant drop in performance, even at low H_2 concentrations.
Valves	Are expected to handle up to 7 bar partial pressure without any modifications, after which they may need to be replaced.

worth noting that many of the benchmarked studies conducted on relatively low-pressure gas networks showed marginal flexibility in tolerating an increased blended H_2 reaching up to 5%–10% concentration limits. Further research and testing through joint industrial programs (JIPs) are ongoing to provide insight into the material H_2 embrittlement with detailed validation and qualification requirements for the industry.

Multiple local network components were assessed to determine the expected limits. The study's findings indicated there was no common limiting H_2 value that is valid for all parts of the natural gas network infrastructure. The blending limits for the various components are shown in **FIG. 2** and summarized in **TABLE 2.**

The illustrated results and findings are related to the first option of injecting H_2 into the natural gas grid. Conversely, blending H_2 at the end-user's battery limit is a viable method to mitigate the constraints. In this case, a dedicated low-pressure H_2 transmission pipeline with properly qualified materials will be utilized to deliver 100% H_2 to end users responsible for making the right blend at their battery limits. The H_2 source could be from blue H_2 production (steam methane reforming with carbon capture and storage) and/or green H_2 (renewable power with electrolysis).

Takeaway. Blending H_2 into the entire natural gas system presents complexities with uncertain risks on pipeline metallurgy and constraints to some end users that use this gas as a feedstock. It is not the most cost-effective option for decarbonization vs. the dedicated H_2 network option, which offers a significantly lower cost per ton and enables targeting selected end users most suited for decarbonization via H_2 fuel usage.

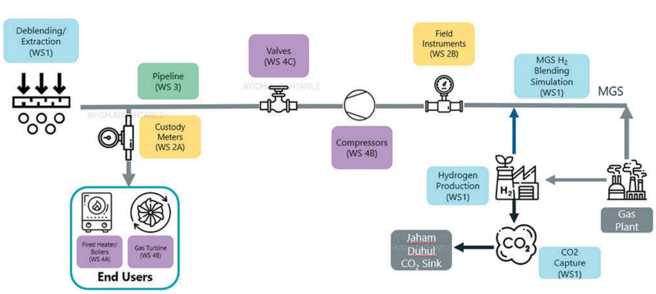

FIG. 1. Overview of the workstreams.

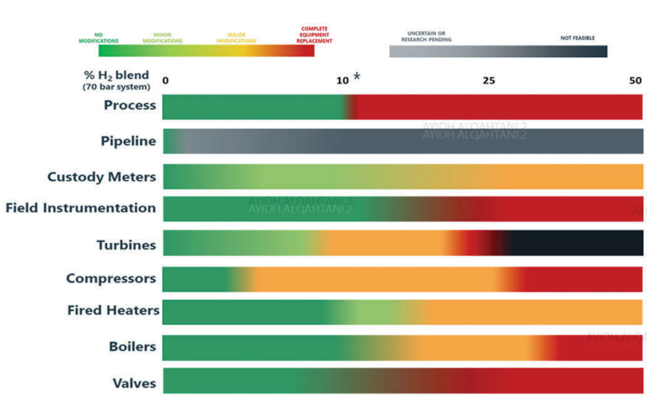

FIG. 2. Local network component heat map H_2 admixture limit.

Alternatively, investing in a standalone H_2 network will minimize the cost required to build larger H_2 production facilities, avoid expensive gas network modifications and allow the flexibility to deliver H_2 at higher concentrations at the end user's battery limits. Therefore, to further develop the dedicated H_2 network that can supply blue and green H_2, a more comprehensive assessment of end users should be undertaken to ensure feedstock users are not impacted.

The gas turbine market should be monitored for developments in the limits of H_2 in existing gas turbine machines. There is also a potential for increased H_2 concentrations without impacting the modification cost, leading to increased decarbonization levels and expanding H_2 supply. Operational expenditure reduction can be capitalized through increased investments in green energy projects across Saudi Arabia, reducing the overall cost of renewable power for H_2 production from electrolysis over the long term. H2T

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TECHNOLOGY SPOTLIGHT

S. SHARMA, Technical Editor

HYDROGEN PRODUCTION

New technologies for green H_2 purification

Shell and BASF have collaborated to evaluate and de-risk BASF's Puristar® R0-20 and Sorbead® adsorption technologies for use in green H_2 production. The two technologies purify and dehydrate the product H_2 stream from the water electrolysis process, which can then be used for liquefaction and transportation, as an energy source or chemical feedstock. According to BASF, the Puristar and Sorbead technologies are in Shell's portfolio for potential use in Shell's global green H_2 projects.

Puristar R0-20 is a versatile catalyst that can remove trace oxygen from the H_2 stream following electrolysis. Sorbead adsorption technology provides a low-energy solution for H_2 dehydration to reliably achieve low water outlet specifications.

The H_2 product stream from water electrolysis contains water and remnant oxygen, which are impurities that must be removed prior to downstream processing or utilization of the H_2. First, the Puristar R0-20 catalyst removes the oxygen by converting it to water in the DeOxo unit. After the DeOxo step, Sorbead adsorption technology is used to dehydrate the H_2.

Following the purification, the H_2 can be used as an energy source or chemical feedstock. Through recent research and development and pilot activities, BASF has created a new DeOxo design tool that focused specifically on optimizing DeOxo units operating downstream of an electrolyzer. This new modeling tool allows for the design of smaller DeOxo vessels, providing capital and operating expenditure benefits to the project.

According to BASF, Puristar R0-20 catalyst operates at low temperatures and with minimal precious metal content in the catalyst. Additionally, BASF Sorbead adsorption provides several advantages for green H_2 applications, including a minimal energy footprint vs. alternative materials, reliability, simple operation, high capacity for water and lower regeneration temperatures vs. activated alumina or molecular sieves, as well a long life, operational turndown flexibility and immediate on-spec gas at startup.

According to BASF, green H_2 is a major component in achieving the common goals of the two companies towards net-zero emissions, and the de-risking of Puristar R0-20 and Sorbead adsorption technologies is an important step in the process.

H_2 EQUIPMENT

Thermal mass flowmeters for H_2 measurement

Fluid Components International (FCI) has launched the ST series thermal flowmeters as rugged flowmeter solutions useful for engineers and plant operators responsible for producing, using, dispensing or distributing H_2 gas. The H_2-calibrated flowmeters provide a range of products for varying pipe diameters and virtually any installation conditions and require no routine maintenance.

H_2-calibrated thermal mass flowmeters are well suited to meet the conditions of these applications. Thermal mass flowmeters work based on the principles of heat transfer. H_2 has a very high heat transfer rate and to measure it with high accuracy and repeatability, a thermal flowmeter should be calibrated in actual H_2. Applying theoretical gas equivalency equations to "correct" readings for H_2 is simply inadequate and ineffective for this gas.

FCI's ST series thermal flowmeters are calibrated under custom installation conditions in H_2 to achieve accuracy and repeatability in their intended application. The direct mass flow measurement and inherently multivariable systems provide both flow and temperature outputs. Thermal mass flowmeters, designed without moving parts, also virtually eliminate wear, breakage and maintenance. The ST series has a wide selection of process connections, including compression fittings, NPT male and female threaded connections, flanges, ball valves, hot taps and more to ensure installation site compatibility.

The ST family offers solutions from small, compact meters with basic 4-20mA analog output to feature-enhanced versions with multiple 4-20mA outputs; digital bus communications such as HART, Modbus, Foundation Fieldbus and Profibus; in-situ calibration; self-checks; and on-board data logging, among others. Furthermore, all FCI ST series H_2 flowmeters measure direct mass flow, carry global agency approvals for installation in Division 1/Zone 1 environments, and offer superior ruggedness and long-life with NEMA 4X/IP 67 rated low-copper content aluminum or 316 stainless-steel enclosures.

Standard turndowns of 100:1 and flow ranges from 0.25 standard ft/sec–1,000 standard ft/sec (0.07 normal m/sec–305 normal m/sec) ensure their application versatility. The ST's transmitter/electronics can be integrally mounted with the flow body or may be remotely mounted up to 1,000 ft (305 m) away. They are available in either DC- or AC-powered versions. Their readout/display options include basic flowrate and totalizer to a best-in-class multivariable digital/graphic backlighted LCD with FCI's exclusive through-the-glass activated 4-button array.

In H_2 applications with limited straight-runs and/or for operating in transitional flow ranges that can adversely affect accuracy and repeatability, ST series flowmeters are also optionally available with and calibration-matched to Vortab® flow conditioners to ensure installed performance.

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H_2 STORAGE AND TRANSPORTATION APPLICATIONS

Long-range trucks powered by H_2 fuel cells in the testing stage

Volvo Trucks has begun to test vehicles that use fuel cells powered by H_2, which have an extended range of as much as 1,000 km (more than 621 mi).

To decarbonize the transportation sector, Volvo Trucks offers battery electric trucks and trucks that run on renewable fuels, such as biogas, and are now adding fuel cell trucks powered by H_2 to its portfolio. A fuel cell generates its own electricity from the H_2 onboard instead of being charged from an external source. The only byproduct emitted is water vapor.

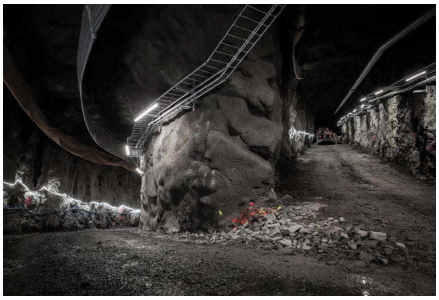
Volvo's H_2 fuel cell technology has been under development and is running successfully on the test track. According to the company, irrespective of transport assignments, the combination of battery electric and fuel cell electric can eliminate CO_2 exhaust emissions from trucks. The technology is expected to be in pilot stage in a few years and become commercially available in the late 2020s/early 2030s. The fuel cell electric trucks will have an operational range comparable to many diesel trucks (up to 1,000 km) and a refueling time of less than 15 min. The total weight can be around 65 t or even higher, and the two fuel cells have the capacity to generate 300 kW of electricity onboard.

According to Volvo, H_2-powered fuel cell electric trucks will be especially suitable for long distances and heavy, energy-demanding assignments. They could also be an option in countries where battery charging possibilities are limited.

Fuel cell technology is still in the early phases of development, with several benefits and challenges—i.e., the large-scale supply of green H_2 and the lack of H_2 refueling infrastructure for heavy vehicles.

According to Volvo, the supply of green H_2 will increase significantly during the next several years since many industries will depend on it to reduce CO_2. Fuel cell trucks will then be an important complement for longer and heavier transports. Volvo has commenced the testing of a fuel cell articulated hauler prototype, as well.

SSAB, LKAB and Vattenfall inaugurate facility for fossil-free H_2 gas storage, steel production



SSAB, LKAB and Vattenfall have inaugurated HYBRIT's pilot facility for fossil-free H_2 gas storage at Svartöberget in Luleå, Sweden. The rock cavern storage facility is the first of its kind in the world. The inauguration ceremony marks the start of the 2-yr test period, which will run until 2024.

The HYBRIT initiative was launched in 2016 by SSAB, LKAB and Vattenfall. The H_2 storage facility will play a very important role in the overall value chain for fossil-free iron and steel production. Producing fossil-free H_2 gas when there is excess electricity and using stored H_2 gas when the electricity system is under strain will ensure a steady production of sponge iron, the raw material behind fossil-free steel.

According to the Swedish Minister for Energy and Digital Development, Sweden will create new jobs by leading the climate change transition, and the HYBRIT project is an example of this transition using green technology and innovation. Building the energy system of the future requires taking advantage of opportunities to store energy and ensure that large energy users can be flexible in their consumption. HYBRIT's H_2 storage design can offer these advantages.

HYBRIT is being developed so that it is in line with the electricity system of the future, with more weather-dependent electricity generation. The storage facility is different than conventional ones and enables the HYBRIT initiative to take a lead in the fossil-free transition. According to Andreas Regnell, Chairman of the Board, Hybrit Development AB and Senior Vice President and Head of Strategic Development at Vattenfall, HYBRIT can become important for facing climate challenges and enabling fossil-free living within one generation.

According to Martin Pei, Chief Technology Officer, SSAB, SSAB can transform operations and cut Sweden's and Finland's CO_2 emissions by 10% and 7%, respectively. The H_2 storage facility is important to ensure stable steel production and a milestone in the development of HYBRIT.

Lars Ydreskog, Senior Vice President of Strategic Projects at LKAB, described H_2 gas and its storage as central to the transition to fossil-free steel. In 4 yr, HYBRIT technology will be used on a large scale in the first demonstration plant in Gällivare, Sweden. The plan is to then build more sponge iron factories. The pilot project will provide valuable knowledge for the continuing work on creating the world's first fossil-free value chain for the iron and steel industry and aid LKAB in achieving its goal of high H_2 production capacity. According to Klara Helstad, Head of Sustainable Industry Unit at the Swedish Energy Agency, the pilot plant is also important to test and understand how large-scale H_2 storage works, which is essential for a fossil-free value chain for the iron and steel industry and a robust future electrical system.

The technology for storing gas in a lined rock cavern (LRC) is well proven and has been used in southern Sweden for about 20 yr for storing natural gas. The technology is taking a step forward with the development of storing H_2 gas, and the storage facility will also be used more dynamically, being filled and emptied at pace with the H_2 production.

The pilot plant has a size of 100 m^3. At a later stage, a full-scale H_2 gas storage facility measuring 100,000 m^3–120,000 m^3 may be required—such a facility will be able to store up to 100 GWh of electricity converted to H_2 gas, which is sufficient to supply a full-sized sponge iron factory for 3 d–4 d.

SSAB, LKAB and Vattenfall have invested \$23.4 MM in H_2 storage alone, with the Swedish Energy Agency contributing more than \$6.5 MM. The following are notable facts about the H_2 gas storage facility:

- Construction of the H_2 gas storage facility began in May 2021. H_2 storage will be tested in the storage facility using known LRC technology. This means the gas is stored underground in a rock cavern with walls that are lined with a selected material as a sealing layer.
- The fossil-free H_2 gas is produced by water electrolysis using fossil-free electricity.
- It is important to construct such a facility in rock that maintains its

- good qualities. For example, the bedrock in Svartöberget consists mainly of amphibolite with elements of pegmatite and red granite.
- The rock cavern in Svartöberget where the gas is stored is about 30 m below ground level and 100 m from the entrance.

Jacobs' research provides roadmap for the future of H_2 plane refueling

Airport owners and operators must plan for the delivery and storage of H_2 if they are to be ready to fuel H_2-powered aircraft. New research by Jacobs provides a roadmap for airports to implement H_2 fueling technologies, building on its work for the Aeronautical Technology Institute FlyZero report *Airports, Airlines and Airspace: Operations and H_2 Infrastructure.*

Due to the length of time it takes to plan, design, consult and implement new airport infrastructure, airports must make provisions ahead of the first commercially available H_2-powered aircraft expected in the early to mid-2030s.

These scenarios can be used by airports and provide a route to scaling up H_2 availability over time. For example, a large airport may start by implementing Scenario 1 for fueling aircraft, while the required infrastructure for the implementation of Scenario 2 or 3 is being built.

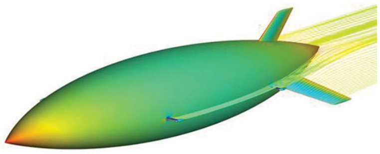
The new roadmap provides airports with steps that can be incrementally implemented to ensure H_2-powered flights are able to take off as soon as aircraft are available. It recommends that airports start with providing airside H_2 gas storage and refueling stations in time for the first flights, before developing more advanced liquid H_2 storage and gas pipelines for fueling planes by the early 2050s.

These sources will be able to provide power beyond the planes and airport infrastructure. The report suggests H_2 gas blending could power heating in terminals by the mid-2040s, eventually moving to 100% H_2 gas heating in the 2050s. If an airport can produce H_2 through electrolysis onsite, it could become an energy hub for its local community. This would provide businesses, public services and homes with carbon neutral power, generating social value.

According to Jacobs' Global Solutions Director for Aviation, an early adoption of fueling infrastructure is critical to the implementation and success of H_2-fueled aircraft. H_2 has the potential to be the core component for the decarbonization of aviation. Airport operators and owners need partnerships with local businesses and other transport operators to initiate the use of H_2 in the immediate term. By incrementally building the H_2 supply and distribution of infrastructure from a short-term starting point, airports can be ready for H_2-powered planes as soon as they are commercially viable.

Emissions generated from flights account for most of an airport's climate impact. Around 80% of global aviation sector emissions come from flights longer than 1,500 km. It is estimated that the use of H_2-powered aircraft could reduce the climate impact of flights by 50%–75%. Airbus has identified a H_2-combustion propulsion system to potentially provide a net-zero commercial aircraft by 2035.

Successful wind tunnel test of H_2-powered Pipeline-In-The-Sky airship



H_2 Clipper, an alternative energy and aerospace company developing uniquely capable H_2-powered airships and end-to-end H_2 infrastructure solutions, has completed a simulated wind tunnel test using computational fluid dynamics (CFD) of its H_2-powered Pipeline-In-The-Sky airship. The analysis confirms that the airship's aerodynamic design achieves an extremely low level of residual drag and is another step in validating the airship's operating performance and the company's cost modeling.

According to H_2 Clipper, the successful CFD analysis is a major milestone for the development of the Pipeline-In-The-Sky airship and one step closer to the goal of providing the fastest, most flexible and efficiently scalable way to transport fuel-grade H_2 to market worldwide.

The H_2 Clipper airship design is the result of radically innovating and re-thinking lighter-than-air flight for global fuel and cargo transport. The airships offer unprecedented speed, payload and cost advantages, including the following:

- 70% lower cost vs. traditional air freighters
- Payloads of up to 277 t
- 7–10 times faster than shipping by truck or cargo vessel
- 100% carbon-free.

H_2 Clipper has received multiple patents for using an airship to deliver liquid H_2 to market, offering economic and logistical advantages over other methods of bulk delivery of H_2. By transporting cheap and clean power produced from renewable sources to markets with high energy demand, H_2 Clipper aims to solve the economical and effective challenges of transporting H_2 from where it can be produced at the lowest cost to where it is most needed. H_2 Clipper anticipates completing the construction of a prototype in 2025, with the goal of flying its first full-sized airship in 2028.

ZeroAvia signs joint development to decarbonize aviation

ZeroAvia, a company specializing in zero-emissions aviation, has signed a joint development agreement with Textron Aviation on the development of ZeroAvia's H_2-electric, zero-emissions powertrains for the Cessna Grand Caravan aircraft. ZeroAvia will obtain a supplemental type certificate to retrofit the Grand Caravan single-engine utility turboprop with the ZA600 zero-emissions powertrain, targeting commercial and cargo operators.

The Cessna Grand Caravan's strong wing design enables the aircraft to mount the H_2 fuel tanks under the wings, ensuring operators can maintain seat capacity or cargo space, while transitioning to zero-emissions propulsion systems.

According to the company's press release, ZeroAvia will develop its ZA600 powertrain system for the Grand Caravan with data, engineering and certification support provided by Textron Aviation. ZeroAvia aims to obtain certification for the 600-kW powertrain as early as 2025, enabling customers to operate zero-emissions flights.

PROJECTS UPDATE

LEE NICHOLS, VP, Content/Editor-in-Chief

GLOBAL TRENDS

According to a report by Global Energy Infrastructure (GEI), approximately 20% of low-carbon H_2 projects being developed globally have taken a final investment decision (FID). Over the past few years, developers have struggled to secure the necessary financing and offtake agreements needed to take FID, despite the increase in global H_2 strategies and initiatives.

Approximately half of the more than 210 projects that have taken FID are in Europe. The EU was the first region in the world to set a H_2 strategy with import and production targets, which were then beefed up by the RepowerEU initiative—this plan calls for 10 MMtpy of green H_2 to be produced in the European Union (EU) by 2030, with a further 10 MMtpy of imports. However, uncertainty around H_2 taxonomy and proposals on additionality are hampering the development of EU projects.

Moving west, the passing of the Inflation Reduction Act (IRA) in the U.S. has made H_2 projects more attractive to developers. The IRA contains several tax incentives for H_2 project developers.

China, which released its H_2 strategy in March, aims to produce 100,000 tpy–200,000 tpy of green H_2 by 2025. At the time of this publication, 16 H_2 projects have reached FID; however, that number is expected to rapidly increase over the next few years.

AFRICA

Namibia plans to develop renewable energy value chain

Namibia has ambitions to become a renewable energy center on the African continent. The country has already announced projects to develop green H_2 production and clean power generation. Hyphen Hydrogen Energy plans to invest more than $9 B to build a 300,000-tpy green H_2 complex in the country. The project, to be developed in phases, will use 5 GW of renewable generation capacity and a 3-GW electrolyzer to produce green H_2. Construction is scheduled to begin in early 2025, with commissioning of Phase 1 by 2027.

French power producer HDF Energy is investing more than $180 MM to build a H_2 power plant in the country. The facility will use solar panels to generate 85 MW of electricity, which will power electrolyzers to produce H_2. Once operational, the additional power generated will enable Namibia to cut electricity imports from neighboring South Africa by approximately 40%.

Globeleq looking to deliver large-scale green H_2 project in Egypt

In September, Globeleq signed a Memorandum of Understanding (MoU) with the New and Renewable Energy Authority, the General Authority for Suez Canal Economic Zone, the Sovereign Fund of Egypt for Investment and Development, and the Egyptian Electricity Transmission Co. to develop a large-scale green H_2 facility in the Suez Canal Economic Zone, Egypt.

According to Globeleq, the project will be developed in three phases. Phase 1 includes a pilot project using a 100-MW electrolyzer to produce green ammonia. Once all phases are developed, the complex will include 3.6 GW of electrolyzers and around 9 GW of solar photovoltaic (PV) and wind power generation. Globeleq plans to develop, finance, build, own and operate the facility.

Fortescue Future Industries proposes large Egyptian investment

Also in Egypt, Fortescue Future Industries (FFI) announced a proposal to build a large-scale wind, solar and green H_2 production complex. According to FFI's press release, the project would include the construction of a 9.2-GW wind and solar facility in Egypt to power a green H_2 production facility. This project is part of FFI's goal to supply 15 MMtpy of green H_2 by 2030.

ASIA-PACIFIC

Technip Energies to build Yuri Green H_2 project

Technip Energies has been awarded an engineering, procurement, construction and commissioning (EPCC) contract for the Yuri Green H_2 Project in Australia. The project being developed by Yara Clean Ammonia and ENGIE in the Pilbara region of Western Australia includes the construction of a 10-MW electrolysis plant and an 18-MW solar PV farm. Once operational, the facility will produce 640 tpy of green H_2. The green H_2 will be sent to Yara's Pilbara ammonia plant to produce green ammonia.

Technip Energies is responsible for the overall project management and the electrolysis plant EPC and startup. Monford Group is responsible for the overall project construction and the PV farm EPC and startup.

Japanese firms plan green ammonia import facility

Four Japanese firms—Idemitsu Kosan, Tokuyama, Tosoh and Zeon—are planning to convert existing storage facilities into a 1-MMtpy ammonia import terminal. The imported ammonia will be used as a carbon-free fuel in the country, as well as a source for H_2. The project is scheduled to be completed by 2030.

China to significantly ramp up H_2 production

According to the China-Africa Hydrogen Forum, China's H_2 production is forecast to reach 100 MMtpy–150 MMtpy by 2060. This production is expected to be generated by a massive increase in solar and wind capacity, which is expected to reach more than 4,800 GW within the forecasted timeframe.

South Korean firms plan green ammonia value chain

Four South Korean companies—Ark Energy, Hanwhe Impace, Korea Zinc and SK Gas—have formed a partnership to develop a green ammonia value chain between Australia and South Korea. The group plans to use Ark Energy's green energy hub in Queensland, Australia to produce up to 1 MMtpy of green ammonia, which will be shipped to South Korea.

Also in South Korea, Jacobs was awarded a contract from Elenergy—an offshore wind farm developer—for a feasibility study on a green H_2 production and import facility. The facility will use renewable wind power from a 1.5-GW offshore wind farm to produce green H_2. Jacob's scope includes a green H_2 market analysis and technology review, the development of a conceptual design and a business case assessment of developing the project. The green H_2 production and import facility is part of South Korea's goal to increase clean energy production in the country's overall energy mix—South Korea's goals are to increase green H_2 usage in energy consumption and power generation by 2050 to 33% and nearly 24%, respectively.

Consortium to study hydro-based renewable power for H2biscus project

Five companies—Samsung Engineering, Sarawak Economic Development Corp., Sarawak Energy Berhard, LOTTE Chemical and POSCO Holdings—signed an MoU to study the potential of suppling at least 900 MW of hydro-based renewable power for the H2biscus green H_2/ammonia project in Sarawak, Malaysia.

According to Samsung Engineering, the MoU will jointly study the power supply capacity and facilities, such as substations and transmission infrastructure, that would be required to supply the project. In addition, the completion of the H2biscus project feasibility study is scheduled to be completed in 2023, with full operations to begin in 2027.

CANADA

Hydra Energy is building the world's largest H_2 refueling station

In late September, Hydra Energy broke ground on what will become the world's largest H_2 refueling station for heavy-duty trucks once completed. The refueling facility is being built in Prince George, British Columbia and will help refuel heavy-duty trucks along the company' Western Canadian H_2 Corridor.

The station will produce 3,250 kg/d of H_2 using two onsite, 5-MW electrolyzers. The facility is scheduled to begin operations in early 2024.

EUROPE

thyssenkrupp to develop H_2-powered direct-reduced iron plant

thyssenkrupp plans to invest $2 B to develop a H_2-powered direct-reduced iron plant in Duisberg, Germany. The Duisberg project will have a production capacity of 2.5 MMtpy. To be completed in 2026, the facility will help replace a portion of the site's coal-fired blast furnace capacity.

Siemens commissions large-scale H_2 generation plants in Germany

In mid-September, Siemens commissioned a large-scale green H_2 plant in Wunsiedel, Germany. The plant uses solar and wind power to fuel an 8.75-MW electrolyzer, which, in turn, can produce 1,350 tpy of green H_2.

Siemens Smart Infrastructure was responsible for the construction of the plant and the creation of an intelligently monitored and controlled power grid. The green H_2 will be used to decarbonize the region's industrial and commercial sectors and transport, and will be distributed by truck trailers on a decentralized basis to end customers mainly within a radius of 150 km–200 km.

Due to the forecasted demand in green H_2, the project developers have already begun talks on increasing the plant's capacity to 17.5 MW. At the time of this publication, no additional information was available regarding future expansion plans.

NextChem to help develop Hy2Use waste-to-H_2 plant and renewable H_2/ammonia facility

Maire Tecnimont's subsidiary, NextChem, was awarded a nearly $190-MM contract for the development of a waste-to-H_2 plant in Italy. The facility—part of the Hy2Use project, which has been awarded Important Projects of Common European Interest (IPCEI) status—will convert 200,000 tpy of non-recyclable solid waste into 1,500 tpy of H_2 and 55,000 tpy of ethanol (production capacities listed are the project's initial phase). The facility will use proprietary technology developed by NextChem's subsidiary MyRechemical. The project's first phase is scheduled to begin operations in 2027.

NextChem was also awarded a pre-front-end engineering design (pre-FEED) contract by MadoquaPower2X, a consortium consisting of Madoqua Renewables, CIP's Energy Transition Fund and Power2X. The consortium is building a renewable H_2 and green ammonia plant in Sines, Portugal.

MadoquaPower2X will use renewable energy and 500 MW of electrolysis capacity to produce 50,000 tpy of green H_2 and 500,000 tpy of green ammonia. The facility is expected to avoid approximately 600,000 tpy of CO_2 emissions in its initial phase.

Per the contract, NextChem will provide pre-FEED engineering services, including early studies, technology and process reviews, modularity and logistics analysis, and front-end loading of engineering required to undertake the permitting and licensing for the project.

McDermott to conduct FEED for Gunvor's Rotterdam H_2 terminal

Gunvor Petroleum Rotterdam has awarded McDermott front-end engineering design (FEED) contracts for its green H_2 import terminal project at the Port of Rotterdam, the Netherlands. According to McDermott, the FEED contracts cover the project's ammonia tanks, inside/outside battery limits equipment and projects, interconnecting pipelines, and tie-ins.

Puglia Green H_2 Valley project takes a step forward

In September, Edison and Saipem announced the acquisition of Alboran Hydrogen Brindisi Srl, a firm that is helping develop the Puglia Green H_2 Valley project in Italy. Saipem also announced that it holds exclusive rights for the implementation of the project.

The Puglia Green H_2 Valley project includes the construction of three green H_2 plants in Brindisi, Taranto and Cerignola. These three plants will have a total combined electrolysis capacity of 220 MW, powered by approximately 400 MW of PV solar energy. Once operational, the three plants will be able to produce up to 300 MMm^3/yr of green H_2.

An expanded version of Projects Update can be found online at www.H2-Tech.com.

The energy transition for the oil and gas industry

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The energy transition is a pathway to achieve net-zero by transforming the energy sector into one that is low carbon while maintaining energy sustainability and security—increasing and utilizing the demand in oil and gas throughout the transition while reducing greenhouse gas emissions. The industry is facing challenges to produce energy in an economical and sustainable way as policy makers seek emissions reductions through carbon pricing and trading. According to an International Energy Agency (IEA) report, the transition of oil and gas should consider three main focus levers: rising demand for energy due to a growing global population; affordable and reliable supplies of liquid and gas, since the industry plays a critical role in economic systems; and reducing the energy emissions contribution in line with the decarbonization movement to achieve net-zero emissions.

The authors' company is not new to the decarbonization industry, as it has built conventional gas plants to treat the gas from the oil wells, resulting in the cleanest gas to replace oil in the power sector. The company has also invested in recovering waste gas to reduce emissions for environmental purposes. The technologies installed to support emissions reduction were mature and feasible both technically and economically. Improving on previous efforts to further the movement toward transition will require governance and policies to control emissions reduction, clean energy product demand, and technologies that are financially mature.

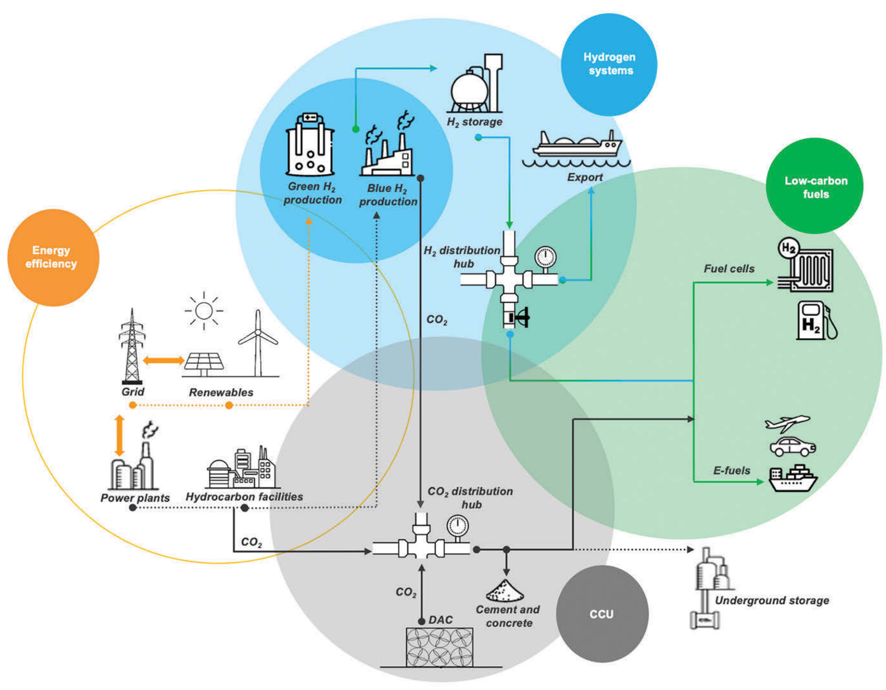

FIG. 1. The four levers of the supply chain toward the energy transition: energy efficiency, a H_2 system, carbon capture and low-carbon fuels.

In line with the energy transition movement, the oil and gas industry should consider investment in carbon capture and utilization (CCU), and produce low-carbon products like hydrogen (H_2) and ammonia (NH_3). Carbon capture will support emissions reduction through flare systems, sulfur oxides (SO_x), nitrogen oxide (NO_x) and carbon dioxide (CO_2) in the boilers, and sulfur recovery unit (SRU) thermal oxidizer stacks. Utilizing emissions to produce low-carbon products will require innovative thinking to support the increasing demand. Carbon capture will also allow the production of blue H_2 as a byproduct from steam methane reformers (SMRs) or H_2 production technologies. H_2 can be utilized either for refueling or to reduce the emissions in the power sector. Analyses show that a beneficial energy transition is more difficult without a supporting government policy shift.

According to the Atlantic Council, recommended steps to support and lead the transition movement in the oil and gas industry include:

- Develop strategies for decarbonization to reduce emissions and ensure profitability
- Support policy development of clear objectives for investors
- Invest in promising projects, technologies, etc., that support achieving net-zero
- Implement approaches to transition oil and gas products to low-carbon products like H_2.

A supply chain toward the energy transition has been developed that will focus on four levers, shown in **FIG. 1:** energy efficiency, a H_2 system, carbon capture and low-carbon fuels.

The energy efficiency lever can play a role in reducing emissions and enhancing energy in the power sector, ensuring that operating facilities supply power efficiently to the grid. Renewables are another way to supply clean power to support the grid and achieve the goals of various clean power initiatives. Establishing energy efficiency as a basis will link this lever with the hydrogen system.

Hydrocarbon facilities have a chance to utilize and convert oil and gas sources to H_2 (as a clean product) but must capture CO_2 sources to achieve blue H_2. Renewable power and electrolysis technology will allow the production of green H_2 from the demoralized water. The produced H_2, whether green or blue, requires storage and transportation routes to supply local demand and exporting purposes.

The captured CO_2 sources from hydrocarbon facilities or the air can be collected in a hub to be directly used in the cement and concrete industries (just one potential opportunity to utilize captured CO_2) or stored directly underground with specific geological requirements.

Additionally, combining a H_2 source (green) with CO_2 can be considered under the low-carbon fuel lever umbrella. These sources have the opportunity to produce e-fuel through several licensed technologies. Within the e-fuel section, H_2 and CO_2 can be converted to methane, diesel, kerosene, gasoline, methanol, DME, etc., as part of synthetic fuel for further utilization. Conversely, H_2 can be directly used to produce power through fuel cells technology or as an alternative product for gasoline within the transportation sector. Converting to or moving with this transition requires a set strategy and technology road map with certain criteria. These options allow the oil and gas industry to map its short- and long-term investments.

Achieving the optimum transition in oil and gas will require investment and innovation to reach decarbonization goals and identify clean sources to reduce Scope 1, 2 and 3 emissions.

Pathways to transition. H_2—which has been playing (and will continue to play) a major role in global strategies towards decarbonization—can be produced in several ways, depending on the feedstock used. Presently, fossil-based H_2 (gray) is the dominant pathway for H_2 production using reforming gasification technologies. Several technologies are available to produce H_2 from fossil fuels at industrial scale: the three dominant technologies are SMR, autothermal reforming (ATR) and partial oxidation (POx).

The existing fossil fuel industry is designed to generate gray H_2 through the reforming process and requires the installation of carbon capture to convert it to blue H_2 to support net-zero emissions.

SMR is the process of reacting methane (CH_4) or natural gas with high-temperature steam as the oxidant in the presence of a catalyst to produce H_2, CO and a relatively small volume of CO_2. This gaseous mixture is referred to as syngas. The reaction is endothermic and requires heat to the process for the reaction to take place, usually by burning additional natural gas into the reformer furnace.

With POx, CH_4 or other hydrocarbons react with a limited amount of oxygen as the oxidant. The oxygen supplied is insufficient to fully oxidize the hydrocarbons to CO_2 and water. Since the stoichiometric quantities of oxygen are lower than required, the products of the reaction contain primarily hydrogen and CO and a relatively small amount of CO_2. If air is used as the oxygen source, then nitrogen will also be present in the reaction products—for this reason, the majority of processes use pure O_2 from an ASU.

ATR is also a common H_2 production technology that combines POx with SMR in a single reaction chamber. The partial oxidation process involves the reaction of oxygen with CH_4. The POx of CH_4 is a noncatalytic exothermic reaction, while the reforming of CH_4 with steam is a catalytic endothermic reaction. The quantity of the oxidant can be adjusted so that the POx reaction provides all the required heat energy for the reforming reaction, eliminating the need for an external input of heat.

When the carbon emissions from the aforementioned processes are captured using CCS technology, then the H_2 is termed "blue" to indicate that it is generated by nonrenewable means—the carbon emissions are offset though the use of CCS.

CH_4 pyrolysis (turquoise) is another pathway to produce H_2 with lower carbon intensity where CH_4 is thermally decomposed into H_2 and solid carbon. Carbon black is a material produced by the incomplete combustion of hydrocarbons that can be used to form commercial products. The technology has the potential to be completely emissions free (including offsite emissions) if the electrical power is delivered to the process from renewable energy sources.

Clean H_2 production (green) can be achieved through the use of electrolysis: electrolyzers use electricity to split water into H_2 and oxygen. A typical electrolysis unit consists of a cathode and anode immersed in an electrolyte. When an electrical current is applied, the water is split and H_2 is produced at the cathode while oxygen is evolved at the anode. The technology is available commercially but requires further development to reduce the cost of H_2 significantly.

CCUS. The authors' company supports global decarbonization through its own initiatives, including the Corporate Decarbonization Initiative, which aims to reduce the amount of carbon emissions that must be managed to reach a carbon balance or net-zero emissions. One of the key methodologies to reduce carbon emissions are carbon capture, utilization and storage (CCUS) technologies, which capture CO_2 emissions at the source or directly from the air. CO_2 emissions are then transported away and stored deep underground or turned into useful products. Capturing carbon has been used for decades to help improve the quality of natural gas. Moreover, new ways to add value to waste CO_2 are being explored by turning the gas into marketable industrial and commercial products.

Carbon capture technologies can be categorized as:

- **Pre-combustion**—Pre-combustion carbon capture involves the removal of CO_2 from fossil fuels before combustion is completed. Examples include coal gasification and SMR, where the feedstock is partially oxidized to form syngas, followed by a water-gas shift (WGS) to produce a CO_2 and H_2 stream, from which CO_2 can be separated.

- **Oxy-combustion**—Oxy-combustion carbon capture, or oxyfuel combustion, refers to combustion with pure oxygen. In this process, the fossil fuel is burned in oxygen instead of air. The resulting flue gas consists of mainly CO_2 and water vapor. The water is condensed through cooling and the result is an almost pure CO_2 stream that can be transported and stored.
- **Post-combustion**—Post-combustion capture involves the removal of CO_2 from flue gas after the fossil fuel has been burned. Post-combustion methods are end-of-pipe solutions for industrial combustion processes. Flue gases for post-combustion capture have anywhere from 5%–15% CO_2 concentration and are near atmospheric pressure.

CCUS technologies can be classified into three phases in case of deployment:

1. **Ready technologies** are CO_2 capture technologies that can be categorized as commercially available or almost commercially available. These technologies have been tested or operated as demonstration projects, or are widely deployed in various commercial applications. In the near or medium term, it is expected that these technologies would involve further development to achieve incremental improvement.
2. **Emerging technologies,** such as emerging CO_2 capture technologies, can be demonstrated at pre-commercial scale and may become commercially available in the coming years.
3. **Concept technologies** are emerging technologies that are considered to be at a low level of maturity with a long lead time to get to market.

Most ready-deployed technologies are based on post-combustion CO_2 capture and are deployed as part of large-scale CCS projects at existing power generation plants. Deployment of CO_2 capture technology has focused on low-cost process emissions-based opportunities, including industrial applications such as natural gas processing, cement, iron and steel, and chemicals, as well as power generation plants. Carbon capture processes can be classified according to their gas separation/capturing principles, namely chemical absorption, physical absorption, adsorption, calcium and reversible chemical loops, membranes, [direct air capture (DAC)] and cryogenic separation.

CO_2 capture activities have mostly focused on power generation plants—mainly coal- and gas-fired power plants—as these comprise the largest stationary source of CO_2 emissions. More recently, industrial applications of CO_2 capture have begun to gather momentum, mainly in the steel and cement industries, and (to a lesser extent) in the oil refining and chemicals industries.

CO_2 storage involves the production and recovery of CO_2 from industrial processes and is typically followed by drying and compression. The captured CO_2 can be injected into depleted oil and natural gas fields as enhanced oil recovery (EOR) or stored as sequestration in other deep geological formations, such as saline aquifers. Alternatively, CO_2 can be used as a chemical feedstock for e-fuel, curing in cement process and algal biofuels production, among a wide range of CO_2 utilization options.

Takeaway. Carbon capture from gas streams is not new. CO_2 capture technologies based on chemical solvents (amines) were first commercially deployed in the 1930s to separate CO_2 and other acid gases from methane in natural gas production. Prior to the early 1970s, all CO_2 captured was vented to atmosphere except for a small portion used or sold for other purposes, such as urea production or beverage carbonation.

The main driver of carbon capture is capture costs or capture abatement in $/MMt of CO_2. The cost of CO_2 capture from low-concentration sources, such as coal-fired power generation, has been reduced by approximately 50% over the past decade and is decreasing for other applications. The cost of CO_2 capture can vary by point source and technology. Fuel transformation applications that produce a concentrated CO_2 stream and/or that require CO_2 to be separated as an inherent part of the process (such as in natural gas processing) have low CO_2 capture costs and have been favored for deployment.

Transitioning from oil and gas to clean energy will require a huge investment. Government policies and regulations, in addition to global awareness, will accelerate the transition to net-zero emissions. Investing in CO_2 conversion and utilization, especially by integrating it with existing facilities, will contribute significantly to emissions reduction. To increase the clean energy supply and demand, companies must invest in technology innovation and digitalization. This will significantly reduce the cost of green technologies, a major challenge for energy transition.

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SPECIAL FOCUS: FUTURE OF HYDROGEN ENERGY

Solid oxide electrolysis cell (SOEC): Potential technology for low-cost green H_2

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Achieving net-zero emissions by 2050 to restrict global temperature rise to 1.5°C continues to be a significant challenge for the global energy sector. According to the International Energy Agency's (IEA's) *Annual Report 2021,* there will be a huge energy transition from fossil fuel to renewables to 2050: it is forecast that almost 90% of electricity generation will come from renewable sources, with wind and solar PV together accounting for nearly 70%. While there will be a significant shift towards electrification, some sectors will be difficult to electrify, such as steel, cement, chemicals, fertilizers, aviation, etc.

Hydrogen (H_2), and specifically green H_2 (H_2 made without fossil fuels), can play a key role in decarbonizing these sectors.

H_2 can contribute to energy security and environmental compatibility as an alternative energy carrier—the energy system has key features that include availability, economic production, transportability, transformability (into other forms of energy) and environmental friendliness. It has the potential to be used as fuel for power and transportation. Electricity and H_2 form complementary options for transferring and storing energy for different end uses, offering much more flexibility in optimizing energy structures on a macro scale. Both are efficient and easy-to-handle and have near-zero emissions when used (considering non-fossil origins).

H_2 combined with carbon dioxide (CO_2) to produce liquid synthetic fuels may also contribute to a reduction in CO_2 emissions. H_2 or H_2-rich liquid fuel (e.g., methanol) can be converted to electricity for transport purposes via fuel cells. Also, it can serve as a feedstock for various chemical reactions to produce a range of synthetic fuels and chemicals, potentially decarbonizing these sectors.

Global H_2 production must rise from approximately 75 MMtpy to 500 MMtpy–700 MMtpy by mid-century to reach net-zero CO_2 emissions targets. Coupling H_2 production with renewables is a viable path to achieve this. More than 95% of today's global H_2 production is from carbon-based, CO_2-emitting methods: natural gas steam methane reforming (SMR) and coal gasification.

Green H_2 can be produced in several ways using renewable energy sources like solar, wind or nuclear (high- and low-temperature electrolysis, various thermochemical and photochemical processes, etc.). However, water electrolysis is the most effective technique and is capturing the market's attention.

The electrolysis of water to produce H_2 has been studied for the last 100 yr. However, at present, only less than 1% of H_2 is produced from the electrolysis of water due to the high consumption of electrical energy required to separate the water molecule because water is a very stable molecule. Nevertheless, as renewable power costs have been decreasing significantly over the years, H_2 production through electrolysis is encouraged, as this route is the most sustainable process for producing H_2.

Several water electrolysis technologies have been developed throughout the years. At present, alkaline electrolysis (AE) and proton exchange membrane electrolysis (PEME) are proven as commercial technologies. However, solid oxide electrolysis (SOE) has attracted many to bring this technology to market to achieve better energy efficiency. Other water electrolysis technologies—like anion exchange membrane electrolysis (AEME) and protonic ceramic electrochemical cell electrolysis (PCECE), among others—are in the development or demonstration stages and are not discussed here.

Low-temperature electrolysis AE and PEME are operated below 100°C, whereas SOE operates at significantly higher temperatures. Despite their lower operating temperatures, high efficiency and technological maturity, low-temperature electrolysis cells cause high electrical energy consumption. Thermodynamically, the electrical energy demand to electrolyze water decreases as the operating temperature increases. Due to this, high-temperature electrolysis like SOE could achieve a 30%–40% reduction in electricity consumption if integrated with external process waste heat. Therefore, high-temperature solid oxide electrolysis cells (HT-SOECs) can produce the most cost-effective energy H_2 compared with low-temperature routes like AE and PEME.

This article explores several opportunities to produce green H_2, mainly focusing on SOEC technology and its advantages and challenges.

WATER ELECTROLYSIS TECHNOLOGIES

Electrolysis is the most straightforward approach now available to produce H_2 directly from water. Water electrolysis is the dissociation of water using electricity to generate pure H_2 and oxygen as a byproduct. In 1789, Jan Rudolph Deiman and Adriaan Paets van Troostwijk first demonstrated water electrolysis using an electrostatic generator. Then, in 1888, Dmitry Lachinov developed a method of industrial synthesis of H_2 and oxygen via electrolysis.

Based on operating temperature, the electrolysis technologies can be categorized into low-temperature electrolysis (LTE) and high-temperature electrolysis (HTE).

Low-temperature electrolysis (LTE). Low-temperature electrolysis of water is presently the most mature method of green H_2 generation. Low-temperature electrolysis is based on either a liquid or a solid polymer electrolyte. The water molecule is dissociated by applying an electrical current in both cases. The operating temperature is restricted to < 100°C.

Alkaline water electrolysis. Alkaline water electrolysis is composed of an anode and cathode separated by a gas-impermeable membrane. The electrolyte, usually an aqueous solution, comprises 20 wt%–40 wt% of sodium hydroxide (NaOH) or potassium hydroxide (KOH) concentration.

While employing electrical energy into two electrodes, water molecules dissociate at the cathode to give H_2 and negatively charged hydroxide ions by reduction. At the anode, hydroxide ions oxidize, and oxygen and water molecules arise, releasing electrons. TABLE 1 provides further details.

Polymer electrolyte membrane water electrolysis. Polymer electrolyte membrane or proton exchange membrane (PEM) water electrolysis is a contemporary development. In this electrolysis, water is electrochemically dissociated into H_2 at the cathode and oxygen at the anode, and a solid proton-conducting membrane separates the electrodes.

During electrolysis, oxidation of the water molecule leads to the formation of oxygen gas and positively charged H_2 ions at the anode. The external power circuit facilitates the flow of electrons while the H_2 ions move to the cathode through the semipermeable proton exchange membrane. At the cathode, these electrons recombine with the two protons to give one molecule of H_2 by the process of reduction. The H_2 gas generated has a very high purity of 99.99%. TABLE 1 provides further details.

High-temperature electrolysis (HTE). HTE is not yet commercialized, but systems have been developed and demonstrated on a laboratory scale. This technology holds promise for the future. HTE is an electrolysis method where steam is dissociated to H_2 and O_2 at temperatures between 650°C and 1,000°C. In electrolysis, system efficiencies increase with increasing operating temperatures. Low-pressure steam (LPS) can be used with reduced efficiency than the mentioned temperature. If this heat source is a clean one—such as geothermal, solar or nuclear—HTE produces H_2 with nearly zero greenhouse gas (GHG) emissions.

SOECs are fundamentally the reverse counterpart of solid oxide fuel cells (SOFCs). Refer to FIG. 1 for the reverse reaction.

DETAILED PROCESS SCHEME

The typical flow scheme of the SOEC H_2 production system is presented in FIG. 2. The system is designed to produce H_2 by using electricity and water. The system's main components consist of SOEC stacks in series and a balance of plant (BOP). The BOP includes a water pump, heat exchangers, steam generator, etc. Water is heated in a series of heat exchangers to recover the heat from the SOEC outlet gas stream. Preheated water is introduced to the steam generator to produce steam and then to the electric heater to superheat steam. To minimize electricity demand and improve SOEC system efficiency, steam is heated in multiple heat exchangers by the exiting H_2 and oxygen streams. However, in case of availability of external steam, the scheme shown in FIG. 2 can be further optimized.

TABLE 1. Main characteristics of AEC, PEMEC and SOEC systems

Electrolysis technology	Alkaline electrolysis	PEM electrolysis	High-temperature electrolysis (SOE)
Anode reaction	$2OH^- \rightarrow 1/2O_2 + H_2O + 2e^-$	$H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$	$O^{2-} \rightarrow 1/2O_2 + 2e^-$
Cathode reaction	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Charge carrier	OH^-	H^+	O^{2-}
Operating temperature, °C	50–80	20–100	650–1,000
Operating pressure, bar	< 30	< 200	< 25#
Anode material	Ni, Ni-Co alloys	IrO_2, Ir-Sn Oxide, Rh, RhO_2	Ni, YSZ/LSM*
Cathode material	Ni, Ni-Mo alloys, Cd, Pb, Cu, Ag, Pt, Pd, etc.	Pt, Pt/activated Carbon, Pt-Pd	Ni/YSZ
Electrolyte material	KOH, NaOH, H2SO4	PEM membrane: Nafion, Flemion, etc.	YSZ [ZrO_2 stabilized by Y_2O_3 (Yttria stabilized Zirconia)], MgO or CaO
Stack lifetime, hr	60,000–90,000	20,000–60,000	8,000–20,000
Current density, A/cm²	Low at 0.2–0.4 because of large resistance across the thick diaphragm and liquid electrolyte	Substantially higher at 0.6–2.0	0.3–4.0 at 750°C–800°C
Maturity	Mature	Commercial	Demonstration
Cell voltage, V	1.8–2.4	1.8–2.2	0.7–1.5
Voltage efficiency, %HHV	62–82	67–82	< 110
Capital cost, € kW_{el}^{-1}	1,000–1,200 (Low due to inexpensive electrode)	High 1,860–2,320 (Platinum-group metals used and corrosion resistant coating are estimated to be 60x more expensive than the cost of AWE per unit area)	> 2,000
Stack energy, kWh/Nm³ H_2	4.2–5.9	4.2–5.5	≥ 3.2

*Perovskite-type lanthanum strontium manganese (La0.8Sr0.2MnO3)
Lab scale development; in general, SOEC available at lower pressure (atm to < 5 bar)

In the electrolyzer, steam is dissociated at 650°C–1,000°C at the cathode to form the H_2 molecules and oxygen ions (water reduction reaction). The oxide ions migrate from the cathode to the anode and release electrons to the external circuit to become oxygen gas via an oxygen evolution reaction. High temperatures are required to thermally activate oxide ion migration and facilitate electrochemical reactions on both electrodes. As a result, the overall efficiency is improved.

- Cathode reaction: At the H_2 electrode-electrolyte interface, the steam is split into H_2 and oxygen ions (Eq. 1):

$$2\,H_2O + 4\,e^- \leftrightarrow 2\,H_2 + 2\,O^{2-} \quad (1)$$

- Anode reaction: Oxygen ions are drawn through the ceramic electrolyte, at the electrolyte-oxygen electrode interface, and oxygen gas generates (Eq. 2):

$$2\,O^{2-} \leftrightarrow O_2 + 4\,e^- \quad (2)$$

The oxygen then flows along the anode while the H_2—along with some steam mixture—passes along the H_2 electrode on the opposite side of the electrolyte. Downstream of the electrolyzer, the H_2-rich product stream is cooled down after exchanging heat with the inlet process stream, and then passes through a separator to separate H_2 from the condensed water stream.

A fraction of the product H_2 is recycled and mixed with inlet steam (5%–10% H_2 in steam) to maintain reducing conditions and avoid oxidation of the nickel in the H_2 electrode. As a result, HT-SOECs can be operated at high current densities that allow large production capacities using comparatively small cell areas. Practically, an electricity-to-H_2 efficiency of about 90% [on a higher heating value (HHV) basis] appears to be realistically achievable.

High temperature is one of the concerns for heat resources during startup. To overcome that, self-heated (by electricity) standby SOECs can be helpful. While giving electricity due to resistance in the cell, Joule heating occurs, keeping the cell in comparatively hot condition and making it easier to use standby SOECs during startup. Conversely, H_2 from an external source may be needed to keep the cathode in reducing conditions during standby mode.

Preheated air or steam can be used as a sweep gas to remove oxygen from the stack. The purpose of the sweep gas is to dilute the oxygen concentration and therefore decrease corrosion of the oxygen-handling components. Pure oxygen can be produced by the stack and would be a valuable commodity if satisfactory materials and coating could be developed to construct the oxygen-handling components.

SOECs use solid ion-conducting ceramics as the electrolyte, enabling operation at significantly higher temperatures. Potential advantages include high electrical efficiency, low material cost and the option to operate in reverse mode as a fuel cell or in co-electrolysis mode producing syngas [carbon monoxide (CO) and H_2] from water steam (H_2O) and CO_2.

A key challenge is severe material degradation due to the high operating temperatures. Current research is focused on stabilizing existing component materials, developing new materials and lowering the operating temperature to 500°C–700°C (from 650°C–1,000°C) to enable the commercialization of this technology. Even LPS can be used to enhance commercialization. Furthermore, even if required, lowering the temperature below 500°C, integrating SOECs with high-temperature processes like conventional reforming, etc., can reduce combined H_2 production costs.

TABLE 1 shows a comparison of SOECs with other commercial electrolysis technologies.

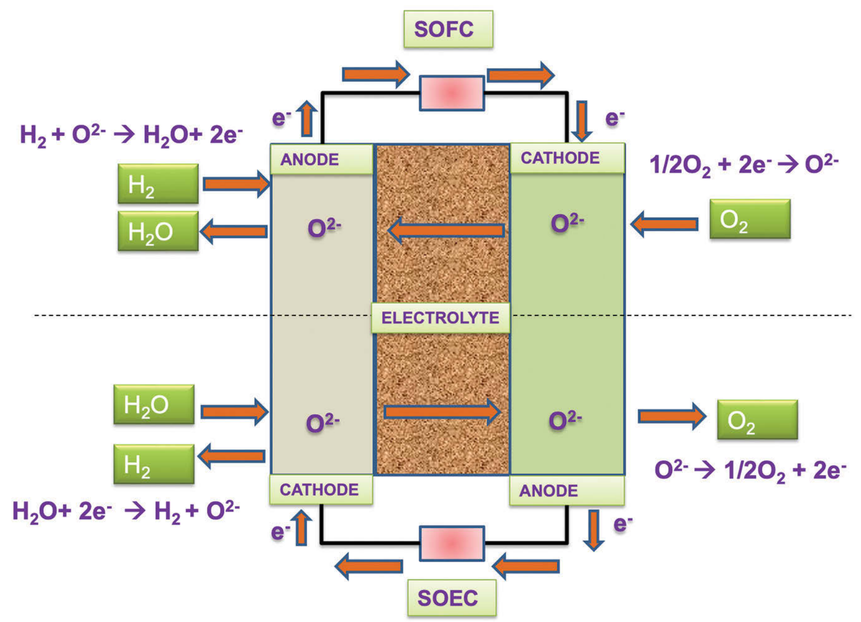

FIG. 1. Solid oxide fuel cell (SOFC) and solid oxide electrolysis cell (SOEC) electrochemical reaction.

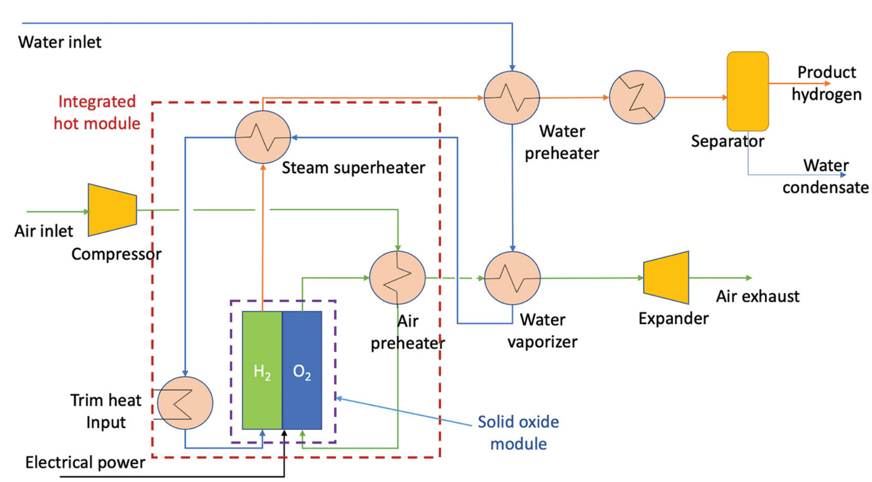

FIG. 2. Typical scheme of SOEC water electrolysis plant.

Thermodynamics of SOECs. From an overall efficiency point of view, electrolysis systems should be operated close to thermoneutral potential. In SOECs, it is possible to operate with a higher current density operation; therefore, a higher H_2 production rate is possible. High-temperature electrolysis of water occurs in the vapor phase, so the total energy demand of electrolysis is reduced by the heat of vaporization. Vaporization can be done by using inexpensive thermal energy rather than electric energy. The Gibbs free energy of formation (for electrolysis reaction) decreases with increasing temperature—decreasing electricity input can be seen with increasing temperature in FIG. 3. Electricity input is ~35% lower than conventional electrolysis in high temperatures at approximately 800°C. The electricity input can be further lowered to ~50% when the temperature is increased to as high as 900°C.

The HT-SOE process is advantageous due to its high overall thermal-to-H_2 efficiency when coupled with heat integration.

Once vaporization is achieved, high temperature is required to superheat steam to achieve high enough ionic conductivity in the electrolyte (steam). This extra heat can be provided by combining a waste heat source, recovering the sensible heat of the produced H_2 and oxygen, and self-heating of the cell due to its inherent electrical resistance.

Temperature-related efficiency gains are far higher for SOECs when steam enters the stack at higher temperature using external heat sources. For splitting steam, SOECs operated at a thermoneutral potential (the potential at which the cooling effect from the endothermic electrolysis process is balanced by the Joule heating caused by the resistances in the cell) of 1.29 V will attain an electrolysis current density of ~1.5 A/cm^2, whereas a PEM electrolyzer operated at a thermoneutral potential of 1.47 V attains a current density of ~0.5 A/cm^2.

Lower cell voltage means lower operational costs (lower electricity demand per quantity of produced gas), while higher current densities are associated with lower capital costs as fewer electrolyzers are needed to achieve the required capacity for gas production when compared with low-temperature electrolyzers. Therefore, the economic motivation for the wider adoption of SOEC technology remains high (FIG. 4).[1]

SOEC materials selection. In the SOEC unit, the electrochemical cell is the main electrolyzer component in which the electrochemical reaction occurs. It is composed of three ceramic layers: a dense electrolyte and two porous electrodes (cathode and anode, where H_2 and oxygen are respectively produced) placed on both sides of the electrolyte. Given the high operating temperature range, the electrochemical cell is made of ceramics (solid oxide membrane electrolyte). For example, Y_2O_3-stabilized ZrO_2 [yttria-stabilised-zirconia (YSZ)] acts as a gas separator and electrolyte. It is used where oxygen ions start migrating from cathode to anode when a voltage is applied. As a result, they show superior ionic conductivity at elevated temperatures.

The electrodes must be both electron

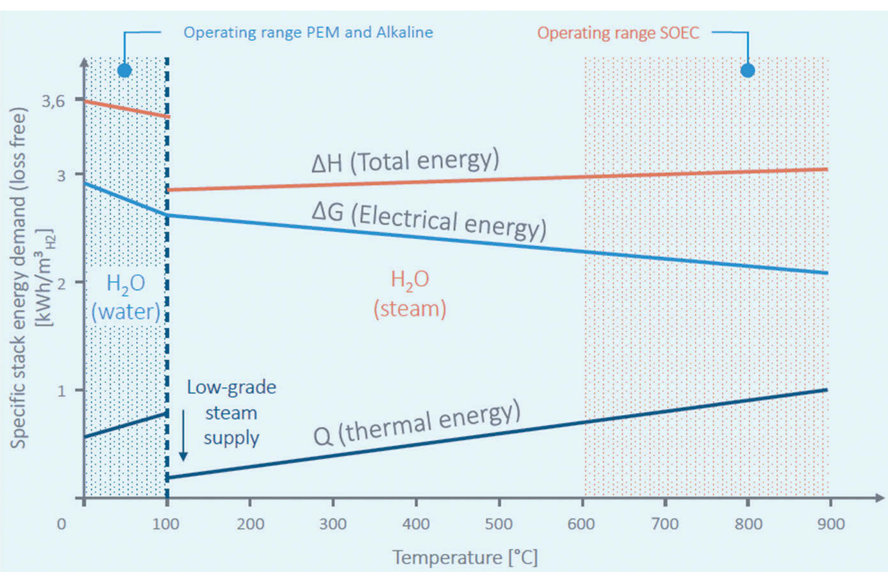

FIG. 3. Energy demand vs. temperature for water/steam electrolysis.

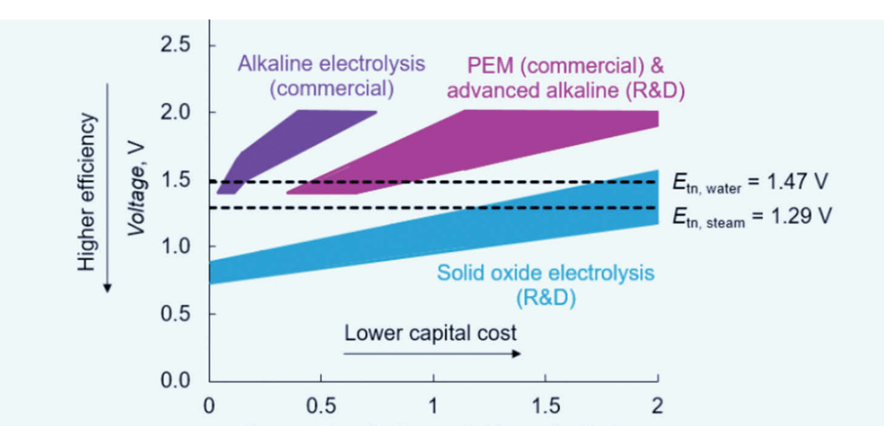

FIG. 4. Typical performance ranges for AE, PEM and SOE technologies for H_2O splitting.

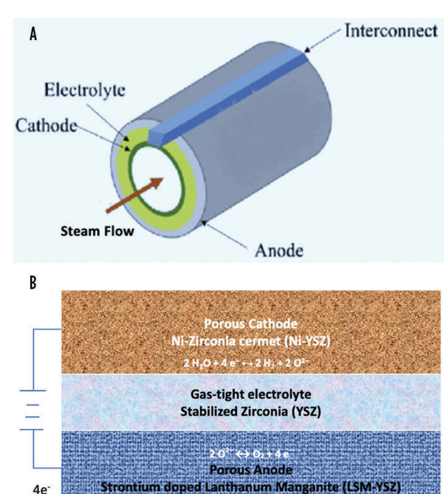

FIG. 5. Schematic SOEC configurations: (A) tubular SOEC and (B) planar SOEC.

and oxide ion-conducting, and maximizing the active surface area is essential for efficient operation. For the H_2 electrode, a cermet (combination of ceramic and metal) of nickel and YSZ is often used with ~30% porosity, whereas a lanthanum strontium manganite (LSM)-YSZ mix is utilized for the oxygen electrode. Materials of different layers are shown in FIG. 5B.

Commonly used SOEC materials are earth-abundant materials, such as yttria and zirconia, which have attracted the use of SOECs. Solid oxide cells providing 1 TW of power in fuel cell mode would require just 1 mos worth of global ZrO_2 production and 21 mos worth of Y_2O_3. In contrast, the same power provided by a PEM fuel cell system would require 53 mos worth of global Pt production.[2]

SOEC configuration. Single cells are the smallest units of SOEC and can be in either tubular configuration or planar configuration, as shown in FIG. 5. In the tubular SOEC, steam is fed through the inside of the tube and reduced to H_2 gas and oxygen ions. The oxygen gas is extracted from the outer layer of the tubular SOEC.

Compared with planar SOECs, the tubular SOEC exhibits higher mechanical strength and facilitates sealing. Tubular SOECs have the specific advantage of high-pressure operation over a planar configuration, although the interconnector design is a challenge (FIG. 5). Despite the larger sealing length between the anode and cathode compartment, the planar cells have better manufacturability and higher electrochemical performance.

The planar SOEC system performed better than its tubular counterpart due to its uniform distribution of gas species on planar SOECs, as well as easier mass production of planar cells—the planar SOEC system configuration is advantageous and should be further investigated. TABLE 2 shows some features of planar and tubular SOEC design.

Cell-to-system configuration. To increase the production rate, the active area of the electrolyzer should be increased. By increasing the single cell dimension, it is challenging to increase the active area; so, many single cells are connected to build a stack. Other than cells, a stack consists of metallic interconnects, glass sealings, flow channels, etc. Several stacks build a module, and several modules build an SOE system of the desired area to achieve the desired production rate.

FIG. 6 illustrates the typical SOEC system configuration from cell level to plant level.

SOEC CHALLENGES AND ADVANCEMENTS

Challenges. The main challenge of SOEC technology that requires further improvement remains the lifetime of electrodes (particularly H_2 electrodes), which are limited by degradation and the long-duration performance of the cells.

One of the main causes of cell degradation is the effect of impurities. In H_2 electrodes, silica-containing impurities can block the electrocatalytically active sites by nonconducting phases, causing degradation and increased polarization resistance. However, cell degradation reduces if the quality of stack inlet gas is maintained.

For H_2 electrodes during long-term operation at high over-potentials (~300 mV), the percolating nickel (Ni) network closest to the electrolyte is destroyed. Ni migrates from the electrolyte electrode interface to the support layer, resulting in irreversible loss of electrochemical performance. For future improvements of SOECs, this must be addressed.

High temperature is also a leading challenge associated with thermal expansion mismatch among different layers and diffusion between layers of material in the cell. Reducing stack operating temperature minimizes interconnect corrosion and the reaction between different stack components.

Challenges also remain in pressurized operations. Low-pressure SOE operation has the advantage of using easily available low-pressure steam at a comparatively lower temperature than that of high-pressure steam. Conversely, pressurized operation can provide several benefits (e.g., pressurization can increase cell power density and reduce the size of auxiliary components). The development of manufacturing techniques and assembling large area cells can reduce the overall cost of a commercial plant.

Advancements. Developments continue in the field of SOECs. Some advancements towards the enduring future of SOECs are discussed here.

Cell level improvement: Current-voltage curves recorded in steam electrolysis reveal that the initial performance of SOECs has increased by more than a factor of 2.5 over the past 15 yr (FIG. 7) due to a drop in area-specific resistance from 0.71 ohm.cm^2 to 0.27 ohm.cm^2 at 750°C. This has been achieved through modifications like improved cell layers' processing, especially the H_2 electrode.

Cell degradation rates tend to decrease over time by a factor of 100 over a 10-yr period. From 2005–2015, cell tests conducted at a current density of 1 A/cm^2 (all cells were supported by a Ni-YSZ electrode and had an active area of 16 cm^2) found a decrease in long-term degradation rate from

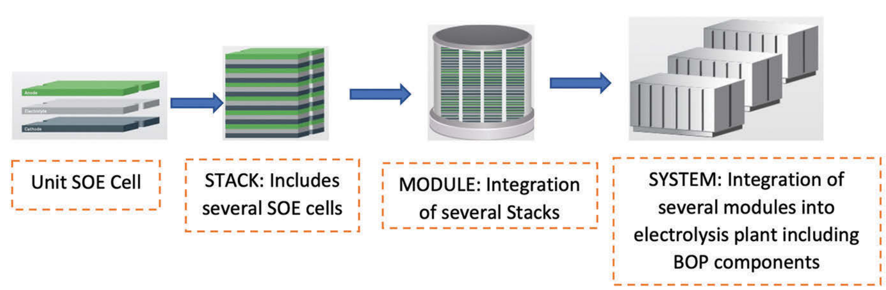

FIG. 6. SOEC system configuration.

TABLE 2. Planar and tubular SOEC design features

Features	Planar design	Tubular design
Power density	High	Low
Volumetric power density	High	Low
High-temperature sealing	Difficult	Easy
Fabrication cost	Low	High
Thermal cycling stability	Low	High

~40%/1,000 hr to ~0.4%/1,000 hr for steam electrolysis.[3] Conversely, alkaline electrolyzer degradation rates are at 1% per 10,000 hr—to reach this level many more improvements are required for SOECs.

Stack level improvement. SOEC stack performance is determined by the performance of cells and other stack components. The properties of each component change during long-term operation under the influence of high temperature. FIG. 8 shows improvement in stack performance from 2009–2019. For steam electrolysis, the stack lifetime tested was limited to < 4 mos in 2009, whereas stack lifetimes of nearly 2.5 yr were experimentally demonstrated in 2019. This is mainly due to an increase in stack durability—SOEC stacks are now less prone to sudden performance failure and degrade less rapidly.

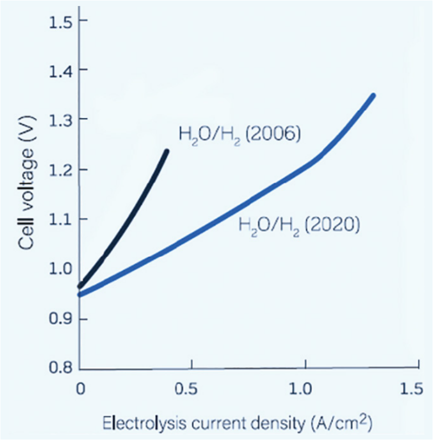

FIG. 7. Cell-level improvements; current-voltage curves for cells fabricated in 2006 and 2020 at 750°C, measured in H_2O/H_2 = 1.

Integrating the SOEC and the heat recovery unit remains a challenge. In addition, the efficiency and cost of the overall plant must be considered for design optimization. In the next section, potential integration schemes are discussed.

SOEC HEAT INTEGRATION WITH WASTE HEAT SOURCES

SOECs operate with high efficiency, especially if fed with high-temperature waste heat. The electrochemical conversion of water permits the storage of both heat and electricity in the produced H_2 form. Green H_2 produced by SOECs can be further processed into synthetic natural gas, methanol, green ammonia, etc., and thermally integrated with a wide range of exothermic chemical syntheses, resulting in further efficiency improvements. Heat integration is also possible with energy sources like nuclear reactors, coal-fired power plants, biomass, domestic waste incinerators, etc. Some of them are discussed here.

SOEC heat integration with diesel engines. Exhaust gas is a high-grade waste heat with temperatures that can exceed 500°C for diesel engines. Therefore, if a diesel engine is integrated with the SOEC system as a heat recovery steam generator (HRSG), it will significantly reduce the power consumption of the SOEC.

Coupling SOEC and ammonia (NH_3) production plants. NH_3 synthesis is an exothermic chemical reaction at relatively high temperatures and pressure (FIG. 9), so a large amount of heat is available for recovery in the plant's energy balance. In addition, the produced H_2 can be used as feed for NH_3 production if mixed with a proper amount of nitrogen (Eq. 3).

$$\tfrac{1}{2}N_2 + \tfrac{3}{2}H_2 \leftrightarrow NH_3 \quad \Delta H_{298K} = -45.7 \text{ kJ/mol (at standard condition)} \tag{3}$$

System integration with an SOE and an NH_3 plant by the Haber-Bosch process operated at high pressure (150 bar–200 bar) and temperature (300°C–500°C) is possible. The ammonia reaction can supply a significant amount of heat energy required by the electrolysis reaction, considering that for each ammonia synthesis, 1.5 mols of H_2 are needed.

Heat integration of high-temperature electrolysis and methanation. The heat of the exothermic methanation reaction can be used entirely for the evaporation of the process water for electrolysis.

The methanation reaction catalyzes H_2 with CO or CO_2 into methane [synthetic natural gas (SNG)] and water (Eqs. 4 and 5).

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_{298K} = -206 \text{ kJ/mol} \tag{4}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2\,H_2O \quad \Delta H_{298K} = -165 \text{ kJ/mol} \tag{5}$$

The exothermic reaction heat of methanation, the cooling of the product stream after methanation and the heat quantity generated by overvoltage (exothermic operation) are greater than the required heat quantity for vaporization and preheating reactant water. Therefore, high efficiencies are achieved by coupling high-temperature electrolysis and methanation (FIG. 10).

Versatile application of SOECs. SOECs can operate reversibly, enabling efficient cyclic conversion between electrical and chemical energy and providing long-term and high-capacity energy storage. In fuel cell mode operation, electricity is generated by oxidizing fuels. In SOEC mode, electricity generates H_2, syngas, etc.

Development is ongoing to directly produce speciality and commodity chemicals other than green H_2. For example, syngas can be produced from co-electrolysis of H_2O and O_2 using high-temperature SOECs. Syngas can

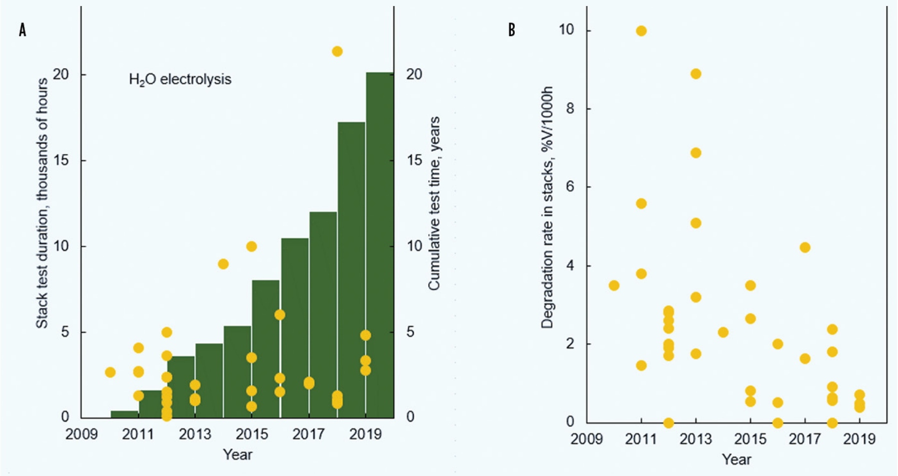

FIG. 8. Stack development over time: (A) stack test duration since 2009, and (B) corresponding degradation rates.

then be converted into a diverse range of chemicals by subsequent catalytic reactions with varying H_2:CO ratios. SOECs are also capable of splitting CO_2 into CO and O_2. Ammonia production by SOECs sending air and steam into the electrolyzer is under development, currently at very low yield. However, ammonia can be used as fuel while operating in SOFC mode for use in marine applications—this is also in development. This versatility in operation makes SOECs superior to other electrolysis modes of operation.

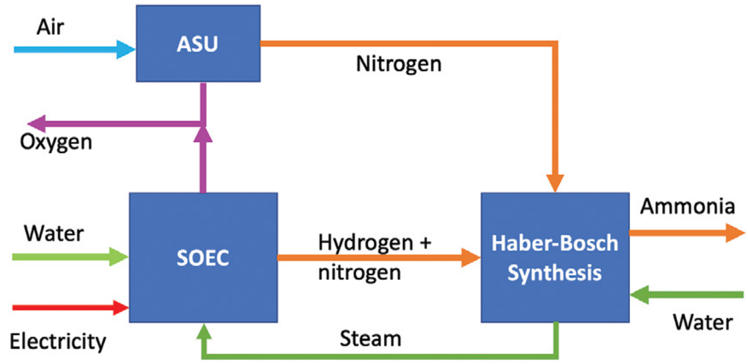

FIG. 9. High-temperature SOEC coupled with ammonia production.

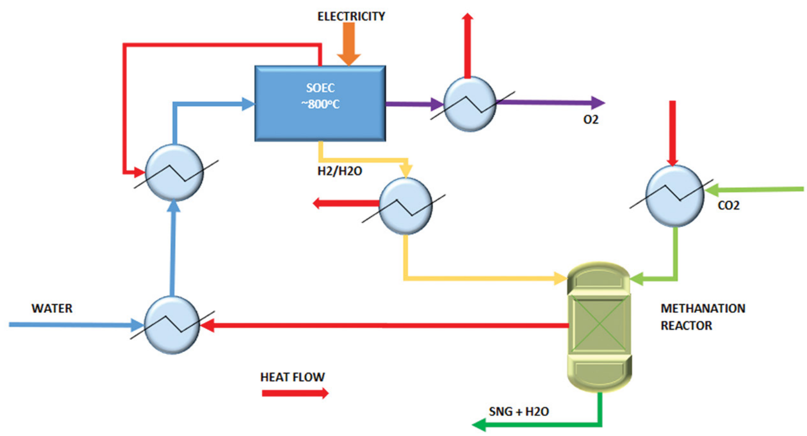

FIG. 10. High-temperature electrolysis coupled with CO_2 methanation.

Takeaways. Reaching net-zero targets calls for significant changes in the ways the energy industry operates, and we are witnessing the movement in that direction. It is widely accepted now that H_2 molecules have the potential to achieve the deep decarbonization of our energy industry, provided we can produce H_2 more sustainably and cost-effectively.

Opinions vary around the globe on how to reach an ambitious green H_2 cost of \$1/kg. We know that the cost of renewable power is playing a significant role in the overall production cost of green H_2, even though electrolyzer technology is one of the key barriers. Several green H_2 projects are being announced around the globe. Alkaline electrolyzers (AE) are in the lead in terms of capacity, which is well-proven and price competitive, followed by PEM electrolyzer technology. Solid oxide electrolzyers are at a small-scale demonstration level. These technologies have achieved enormous improvements driven by advances at the cell, stack and system levels.

Some specific features make SOE technology unique compared to other commercially proven technologies, such as AE and PEME. For example, SOECs operate at 700°C–850°C, and the thermodynamically water split reaction requires a lower Gibbs free Energy (ΔG) at such a high-temperature, making this process highly efficient. Moreover, integrating an external waste heat source like low-pressure steam from an industrial source can help lower electricity demand, depending on the supply temperature. In addition to green H_2 production, the same technology can be applied to various other processes directly producing end products like ammonia, methanol, SNG, etc.

The main electrolyzer components, like electrolytes and electrodes, are made of ceramic materials due to the high operating temperature. These SOEC materials are earth-abundant, so scaling up will not pose any challenge in terms of materials availability. Also, the possibility of SOECs working in reversible operation so a single unit allows for both energy storage and generation permits a complete green power plant to achieve zero-energy building and carbon neutrality targets.

Commercial SOEC electrolyzers are at the kW level, and demonstration units larger than 3 MW are under execution. To see the full potential of SOEC technology, much lower levels of cell degradation at higher current densities must be demonstrated. Moreover, to achieve commercial scale-up, further work is needed in manufacturing and assembling cells to reduce the unit's overall cost.

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Complete references are available online at www.H2-Tech.com.

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Water intensity is tantamount to carbon intensity for climate-friendly fuels

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Any serious undertaking to combat climate change requires fuel production with a negative carbon intensity, but an often-overlooked consideration is water usage. Traditional energy production requires extensive water usage. Power plant cooling systems and hydraulic fracturing can use reclaimed or recycled water.

However, what about new energy generated with water? Much of the attention on renewable hydrogen (H_2) focuses on electrolyzers that use electricity generated from solar and/or wind power to split water molecules into H_2 and oxygen. The term green H_2 has become synonymous with the electrolyzer process. Green H_2 sourced from renewable power is touted as being free of greenhouse gas (GHG) emissions. However, is an energy source truly sustainable if it entails a heavy water usage footprint?

According to "The Water Planetary Boundary: Interrogation and Revision," we use nearly 70% (2,800 km^3) of the planetary boundary of 4,000 km^3/yr of freshwater consumption.[1] Furthermore, the International Energy Agency (IEA) estimates that total water demand for H_2 could equate to 12% of the energy sector's water consumption. In addition, the IEA's 2021 Global Hydrogen Review[2] found that to use seawater instead of fresh water, the cost of desalination must come down, or researchers must find a way to process seawater without corroding equipment.[2] In short, using more water—a limited vital life-sustaining resource—to produce energy is suboptimal.

Nonetheless, electrolysis is being widely pursued for green H_2 production, which seems oxymoronic when considering its source of H_2 feedstock. To avoid using fresh water, another option being pursued is utilizing wastewater. That, of course, will require a water purification process, adding a significant step.

What if solid or gaseous waste was directly used as a feedstock instead of renewable power and water to support H_2 production? This could be solid municipal waste filling landfills, green/food waste that generates methane (CH_4) or fugitive CH_4 emissions waste from conventional oil and natural gas operations.

The term waste-to-energy often connotes incineration, which only adds to the GHG and criteria pollutants' emissions problem that needs many forms of abatement, such as direct air capture technologies being pursued by many companies. There are more convenient, shovel-ready ways to tackle waste. For instance, some waste management companies are already expanding their renewable natural gas production, which entails capturing CH_4 with wells embedded into completed sections of landfills.

There is no single CH_4 abatement and capture solution, and the widespread need for containment requires an all-hands-on-deck response. The author's company has a modular, non-combustion steam/CO_2 reforming system that processes CH_4 into H_2-rich syngas (~60%), which can be upgraded into transportation grade H_2, sustainable aviation fuel, renewable diesel or methanol. No added water is needed; it can process multiple feedstocks at once, without separation, with a moisture content of 30%–55%.

A simple way to visualize this is with a simple takeout food container. The organic material in leftovers, paper-based and plastic food containers can be left together, dumped in a landfill and then converted to produce a negative carbon intensity fuel. The process is emissions free, as well as the clean H_2 it produces. Alternatively, higher energy, lower emissions synthetic fuels can be produced this way, as well.

This presents a solution to a global problem, too. The World Bank estimates that urban populations generate more than 2.2 Btpy of solid waste, and projected population growth would bring that figure to 3.88 Btpy in 2050. That is a lot of feedstock for non-combustion steam/CO_2 reforming to produce clean energy where the waste is generated.[3]

The author's company intends to install its gas-to-gas technology in the spring of 2023 in California; this technology can produce 4,500 kg of H_2/d from renewable or natural gas. It can utilize stranded, flared, low CH_4 landfill gas or otherwise unmonetized gas to create affordable H_2 efficiently.

In addition, the company recently trialed its full-scale second-stage equilibrium steam/CO_2 reformer at its California manufacturing facility, demonstrating methane conversion to transportation-grade H_2 at a rate exceeding other commercially available technologies, such as steam methane reforming.

The Fischer-Tropsch method for synthetic fuels is well-established with coal, but instead of mining for resources, the author's company applies the process to garbage and other waste streams to produce diesel, Jet A, Jet B and military-specified JP-8 aviation fuels from waste. Fischer-Tropsch creates fuels out of H_2 and carbon, as opposed to conventional fuels refined from existing hydrocarbons. In other words, Fischer-Tropsch synthetic fuels are combined instead of taken apart. As a result, these synthetic fuels are higher purity and burn cleaner. Unlike biofuels that depend on food crops, synthetic fuels based on waste provide the dual benefit needed to improve the environment.

The steam/CO_2 reforming process converts 100% of waste. In addition, about 15% of feedstock is converted into a solid bio-carbon, which can potentially be sold as a soil amendment.

The urgency around climate action calls for solutions to the so-called energy trilemma: securing supply to meet the demand that is affordable and sustainable. The energy transition will cost money as capital is needed to build out renewable infrastructure, and higher costs will place a heavier energy burden on low-to-moderate income earners. That is why finding the most cost-effective ways to meet the growing demand for clean energy is crucial.

The beauty of using waste for energy is that it is plentiful, renewable and relatively inexpensive. No additional energy is needed to produce the energy, and no water needs to be added to the process.

Waste is ubiquitous, so H_2 production from waste can be handled locally, near or adjacent to demand, be it for transportation, power generation or industrial usage. This way, waste-to-H_2 also eliminates the need for long-distance H_2 pipelines or waterborne ammonia tankers to carry H_2 to markets, and that cuts out the need for expensive infrastructure buildout.

The old adage of thinking globally and acting locally remains true. Waste-to-energy creates local fuel from local waste. By shortening fuel supply chains, efficiencies are gained and decarbonization deepens. This raises the prospect of reducing dependencies on fuels shipped among regions and eliminates the need for new investments to build and maintain pipelines. The local waste-to-local fuel dynamic offers the possibilities of more affordable, sustainable and secure energy.

An economy-wide energy transition is not happening overnight, and some nascent technologies are far from commercialization. As the world seeks sustainable solutions to the climate crisis, industry must recognize that the need for energy with a negative water intensity is as crucial as the need for energy that has a negative carbon intensity.

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Eight guidelines for planning a H_2 blending pilot at a power generation facility

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H_2 is emerging as a pivotal fuel source for utilities seeking to decarbonize their existing power generation assets, and it is easy to understand why. H_2 is a clean-burning fuel that can be produced from a variety of zero- or low-carbon sources. When combusted, it releases no carbon-related emissions, making it a front-runner to reduce the volume of natural gas relied on as fuel. It also has the potential to help existing power generation assets transition into the rapidly evolving decarbonization landscape.

However, before committing funds to full-scale H_2 retrofits, utilities must first consider some fundamental questions. How will plants respond when H_2 is introduced as a fuel source? What modifications will the system require to utilize H_2? How will the introduction of H_2 affect performance and emissions?

To learn the answers to these and other questions, some utilities have begun pilot programs to blend H_2 fuel into the natural gas supply at existing gas turbine and reciprocating engine sites. These short-duration tests are designed to assess everything from equipment efficiency to the viability of environmental sustainability goals.

FIG. 1. Eight key items to consider when developing a H_2 pilot test.

The protocols for these pilot tests are complex. Even a 1-wk pilot test can take 1 yr to plan, design and implement. Success depends, in part, on the ability to integrate the testing infrastructure with the existing operational system. The following are several key items to consider when developing a H_2 pilot test (FIG. 1).

Safety comes first. H_2 has some unique properties that must be considered. It is nontoxic, colorless and odorless. Because it is the first element on the periodic table, it is approximately 14 times lighter than air. H_2 is also flammable in a wide range of air concentrations, making it easier to ignite than other fuels, if not handled safely. Interestingly, if a H_2 source ignites, the flame burns on the ultraviolet portion of the light spectrum, making it nearly impossible to see. This factor could result in requirements for special flame detector equipment.

Other precautions are also essential for a safe and successful pilot test. For example, consider that the fuel systems at many existing power generation facilities were originally designed only for natural gas. Because H_2 molecules are significantly smaller than methane molecules, leakage may occur through various flanges, gaskets and valves when H_2 is introduced into these systems. Due to the potential presence of leaks, appropriate H_2 leak detection will be necessary in any enclosed areas or areas with a potential ignition source.

Safety starts with planning and engineering design, including the performance of a hazard and operability (HAZOP) study and other safety reviews, long before H_2 is introduced into the facility. A completed safety review helps facilitate assessment of the system design, operating and safety procedures, and emergency response plans. Additionally, the safety review assesses whether applicable codes and standards, such as the National Fire Protection Association (NFPA) 2–Hydrogen Technologies Code, are being followed appropriately.

If an identified hazard cannot be fully mitigated by elimination, substitution, engineering controls or administrative controls, personal protective equipment is used as the last line of defense when working with or around H_2.

Original equipment manufacturer (OEM) coordination is essential. OEMs for gas turbines and reciprocating engines have the greatest knowledge about the H_2 fueling capabilities and requirements of their equipment. OEMs can apply insights garnered from burning H_2 in a lab environment to better understand the impact that H_2-blended fuels have on equipment performance and combustion emissions. Their input is essential in developing effective test plans, including the rate at which the blend ratio of H_2 to natural gas is adjusted.

OEMs are eager to participate in these discussions since they have a stake in the results. It is valuable to obtain more data about how in-service units function when an alternate fuel is introduced over a range of operating scenarios, both when retrofitting installed equipment and when designing future engine and turbine models with 100% H_2 capabilities.

Determine the source and type of H_2. For these projects, H_2 is typically delivered by trailer in either a liquid or gaseous form. Onsite H_2 generation is possible but usually not feasible for most pilot projects. Delivery via a local H_2 pipeline may also be an option if a plant is close to the supplier's distribution system, but this option also presents unique challenges that make it an unlikely source of H_2 for a pilot test.

Today, many industrial gas suppliers are set up to provide H_2 in relatively small quantities for short-term applications or on a long-term, recurring basis. For example, a single trailer delivery of liquid H_2 for a typical industrial customer might be enough for a 6-mos supply. For these pilot power projects, however, a test may require as many as six gaseous or two liquid trailers for a weeklong testing operation. A high-level comparison between gaseous and liquid H_2 deliveries is detailed in **TABLE 1.**

After determining the amount of H_2 required for a test, the next step is to identify the source and type of H_2 to be used. The type of H_2 chosen impacts the design of the overall blending process. The equipment setup for gaseous H_2 is much simpler than that for liquid H_2. High-pressure gaseous H_2 can be connected directly to the blending system, whereas liquid H_2 must be vaporized and its pressure increased before it can be injected into the fuel system. While liquid H_2 can be stored at significantly higher quantities and lower pressures than its gaseous form, it is extremely cryogenic, meaning it must be kept at an extremely low boiling point temperature near –423°F (–253°C).

From a pilot testing perspective, the color of H_2 used is less relevant since it does not impact the equipment's operational functionality during the short test period. The designated H_2 color (green, blue or gray) is indicative of the carbon emissions created during its production. Today, most H_2 suppliers typically provide gray H_2, which is produced using traditional methods (e.g., steam methane reforming) for pilot tests.

Secure H_2 early. Since pilot tests are predicated on timely deliveries of H_2 and the large volume needed for the test duration, orders must be placed early. Even a single turbine or engine test can require a significant amount of H_2 over a brief period. Determining the test volume required will help expedite coordination with industrial gas suppliers on H_2 deliveries that could be limited by quantity and geographic location.

Logistics will evolve over time to address supply chain challenges as utilities consider H_2 supply options that meet their long-term environmental and financial goals. Instead of sourcing H_2 externally in the future, utilities could produce it onsite via the electrolysis of water. Water electrolysis is a mature technology process that utilizes an electrical current to divide water molecules into oxygen and H_2. When coupled with wind, solar or other renewable energy sources to produce electricity, water electrolysis generates zero carbon dioxide (CO_2) emissions. Until this method of H_2 production becomes more widespread, expect a significant increase in liquid or compressed gas H_2 deliveries to accommodate pilot testing.

Location. The NFPA's rules for sitting H_2 storage are detailed in NFPA 2–Hydrogen Technologies Code, which provides minimum setback requirements for both liquid and gaseous H_2. Gaseous H_2 system setbacks are based on storage pressure and piping size, while the setbacks for liquefied H_2 systems are based on storage volume.

During the conceptual design phase, each pilot testing site should be evaluated to determine the appropriate placement of H_2 trailers and other equipment to facilitate testing while maintaining the required spacing. NFPA 2 setbacks impact the transportation of H_2 trailers in and out of the plant site, as well. Depending on the space constraints at the facility, this may also impact the choice of liquid or gaseous H_2 for the test.

The placement of tie-ins and equipment for H_2 blending matters. Tie-ins to the plant's natural gas system must be located in ways that minimize exposure to existing components not originally designed for H_2 usage. Adequate pressure, temperature and flow conditions per OEM requirements, along with pertinent safety devices, are also required in these locations.

These pilot projects typically require two natural gas tie-ins: one to supply natural gas to the blending system, and the other at the point where the H_2 and natural gas mixture from the blending system is injected into the existing fuel gas pipe. The blending system typically consists of a H_2 transfer system, flowmeters and control valves (**FIG. 2**).

TABLE 1. A high-level comparison between gaseous and liquid H_2 deliveries denotes critical factors for each

Parameter	Gaseous	Liquid
Approximate trailer capacity (each)	660 lbs–880 lbs	~7,500 lbs
Maximum allowable working pressure (MAWP)	2,400 psig–2,600 psig	150 psig
Operating temperature	Ambient	–423°F (–253°C)
Trailer dimensions, l × w × h	40 ft × 8 ft × 12 ft	40 ft × 8 ft × 12 ft
Additional equipment required	Pressure regulation Blending components	Pump (or compressor/vaporizer) Blending components

Note: The properties in the table are typical conditions and may vary based on individual hydrogen suppliers.

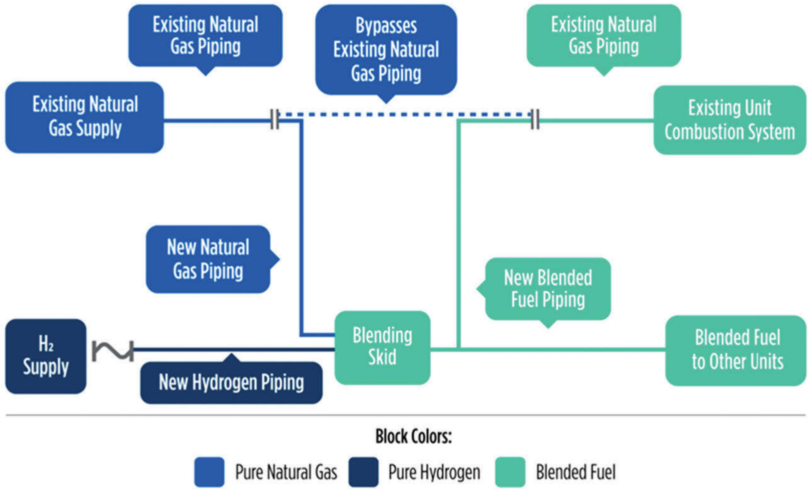

FIG. 2. This schematic of a pilot testing blend shows the anticipated flow process.

An important goal of these pilot tests is to learn how the gas turbines and reciprocating engines react to changes in fuel composition or incomplete mixing. For example, while it is understood that the introduction of H_2 to a natural gas fuel stream changes combustion dynamics, less is known about how the equipment will respond to an imperfect mix of H_2 and natural gas. These projects are expected to assess the equipment's tolerance for these changes, as well as for various H_2 and natural gas concentrations.

H_2 blending pilot tests can impact other plant operations. H_2 may also impact the operation of utilities, equipment and other systems in an existing plant. A balance of plant evaluation is necessary to determine H_2 blending tie-ins, as well as any changes needed to piping, control systems, electrical infrastructure or safety systems, such as fire and gas detection. Impacts to other operating units at the site should also be considered when adjusting emissions controls for the tested unit(s).

Depending on where and how the pilot connects to the plant, operations may be affected in other ways, as well. For example, when working in a plant with multiple engines or turbines, it is preferable to isolate the H_2 test to one unit while the other units are in an outage for the test duration. A pilot test that ties into the common fuel gas header may have a greater impact on overall plant operations than one tied directly into the unit being tested. The time and complexity needed to set up for the pilot test and restore the system after its completion must also be accounted for during the plan's development.

Permanent conversion and permit reevaluation raise new questions. Utilities considering permanent H_2 installations may face other unknowns. Permitting agencies' reactions to pilot tests and future installations are uncertain since there is almost no precedent for them to follow. On one hand, the blended fuel will enable plants to lower CO_2 emissions. On the other hand, permits were issued based on the use of the original, unblended fuel.

The main unanswered question is: Will permitting agencies allow blended fuels under existing permits, or will permit modifications be allowed? Now is the time to begin conversations with permitting agencies on the ramifications of potential permit changes related to H_2 blending.

Takeaway. The source of H_2, storage location and tie-in locations—while keeping safety first and foremost—are major factors that will be crucial to the successful completion of the pilot testing protocol.

The goal for each test may be different for every facility. Some may be interested in understanding H_2's impact on equipment performance, while others may be curious to learn how the presence of H_2 impacts CO_2 and nitrogen oxides emissions. Regardless of the test objective, a H_2 blending pilot can provide insights into the potential challenges that must be overcome and the changes that must be made to current operations. Successfully navigating these challenges will set the stage for future, H_2-based power generation innovations.

Billing accuracy for H_2 vehicle refueling stations

M. SADRI, TÜV SÜD National Engineering Laboratory, Glasgow, Scotland, UK

H_2 is recognized as playing a crucial role in reducing global carbon dioxide (CO_2) emissions. From transportation to heating homes, H_2 is already expected to play a significant part in replacing fossil fuels in net-zero policies in the UK and around the world. There are plans for partial or full replacement of natural gas with H_2 in natural gas grids, as well as ambitious targets to enhance the production of fuel cell vehicles and the development of H_2 refueling stations (**FIG. 1**). These will form the infrastructure of a future H_2 network. Accurate metering of H_2 at different points of this network is crucial, especially when H_2 is transferred from one party (a seller) to another (a buyer).

Fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEV) are considered the most promising candidates for the future of transportation. FCEVs are EVs that use H_2 as fuel. H_2 reacts with oxygen in a reverse electrolysis in their fuel cells to generate the required electricity. This process is free of carbon emissions, with the only byproduct of the reaction being water. FCEVs offer significant advantages, especially for larger vehicles such as buses and heavy goods vehicles. The H_2 tank of an FCEV (small or large) can be filled in a few minutes vs. hours to charge a BEV. However, increasing the use of FCEVs requires the development of relevant infrastructure such as H_2 refueling stations, and technologies such as accurate H_2 flowmeters and regulations. All these aspects are in their early stages of development but growing at a fast pace.

H_2 is sold based on mass (in kilograms) in H_2 vehicle refueling stations. However, accurate billing needs accurate metering of H_2, which is a challenge. Liquid fuels such as petrol (gasoline) and diesel must be measured to 0.5% accuracy in the refueling stations based on the recommendations of the International Organization of Legal Metrology (OIML) (Accuracy Class 0.5 in the document OIML R117). The required accuracy for the measuring system of gaseous fuels such as compressed natural gas is 1.5% (Class 1.5 in OIML R139). However, OIML R139 separates H_2 from all other types of gaseous fuels and recommends Class 2 and Class 4 (2% and 4% accuracy of the measuring system, respectively) for its measurements. It is expected that many counties will enforce Class 2 of OIML R139 in the coming years.

There are several factors that make H_2 metering challenging at H_2 refueling stations. H_2 has a very high gravimetric energy density of 140 MJ/kg. This means that it stores a lot of energy relative to its weight, much more than natural gas (53.6 MJ/kg), diesel (45.6 MJ/kg) and lithium-ion batteries (< 5 MJ/kg). In volumetric terms, H_2 is the least dense of any gas and takes up more space than both natural gas and diesel.

To improve its efficiency as an energy carrier, H_2 is compressed to pressures as high as 700 bar in H_2 vehicles. In this compressed state, H_2 occupies about the same space as a battery, for much less weight. Another advantage to H_2 vehicles is the fast refueling time. However, when H_2 is rapidly compressed to 700 bar, a lot of heat is generated. To stay within safe operating limits, the quickest fuelling protocols pre-cool the gas to –40°C.

Hydrogen refueling stations are therefore required to operate across a wide range of pressures (up to 875 bar) and temperatures (–40°C–60°C). This is very challenging from a measurement perspective, since the accuracy of most flowmeter technologies is adversely affected by extreme pressure and temperature conditions, as well as the transient flow encountered for vehicle filling.

Coriolis meters have dominated the market of H_2 dispensers. They have several advantages, but the most important one might be their capability of mea-

FIG. 1. View of a H_2 refueling station.

suring the mass flowrate directly. The author's company has extensive experience and knowledge in the application of flowmeters for H_2 measurements, as well as other types of gas. In an ongoing joint research project, the author's company is involved in the European project of Metrology for Hydrogen Vehicles II (MetroHyVe II), along with several national or designated measurement institutes and companies from the industry.

As a part of the first MetroHyVe project, several experiments were undertaken on commercially available Coriolis meters for the application in H_2 dispensers (produced by various manufacturers). Results showed that these meters are not sensitive to pressure effects but can be significantly affected by temperature changes, especially before thermal equilibrium is reached between the flowmeter body and the incoming gas—i.e., when pre-cooled gas is suddenly introduced to a meter that is at ambient temperature.

The project highlighted other major sources of error in H_2 dispenser billing. When a customer finishes the refueling of an FCEV, some H_2 is trapped between the meter and the head of the dispenser that connects to the vehicle. This amount of H_2 is measured by the meter but not received by the customer. Some of the trapped H_2 that is in the hose of the dispenser must be vented for safety reasons. The rest remains trapped between the meter and the cutoff valve until the next customer starts refueling. Therefore, each customer receives some H_2 metered for the previous customer and leaves some for the next. However, these two amounts are not always the same as different people might refill their vehicles to different pressures. Hence, a different amount of H_2 is trapped each time. This effect is not related to the flowmeter accuracy but can introduce a significant error in the metering and billing of H_2 for each customer, particularly when there is a large distance between the flowmeter outlet and the dispenser.

H_2 refueling station design considerations and appropriate corrections can be employed to mitigate the uncertainties caused by the aforementioned factors. Finding the right location for the installation of the meter, optimizing the dispenser to reduce the dead volume, and developing and using proper correlations to compensate for the remaining dead volume and the vented H_2 are some solutions. Results of the MetroHyVe project and the author's company's research suggest that, if these considerations are in place, available flowmeters produced for the application in H_2 dispensers can achieve OIML R139 Accuracy Class 2. The author's company has also developed the UK's first mobile primary standard for field evaluation of H_2 refueling station dispensers. This primary standard can be taken to a H_2 refueling station to test its dispensers and determine if the metering systems can meet the requirements of OIML R139.

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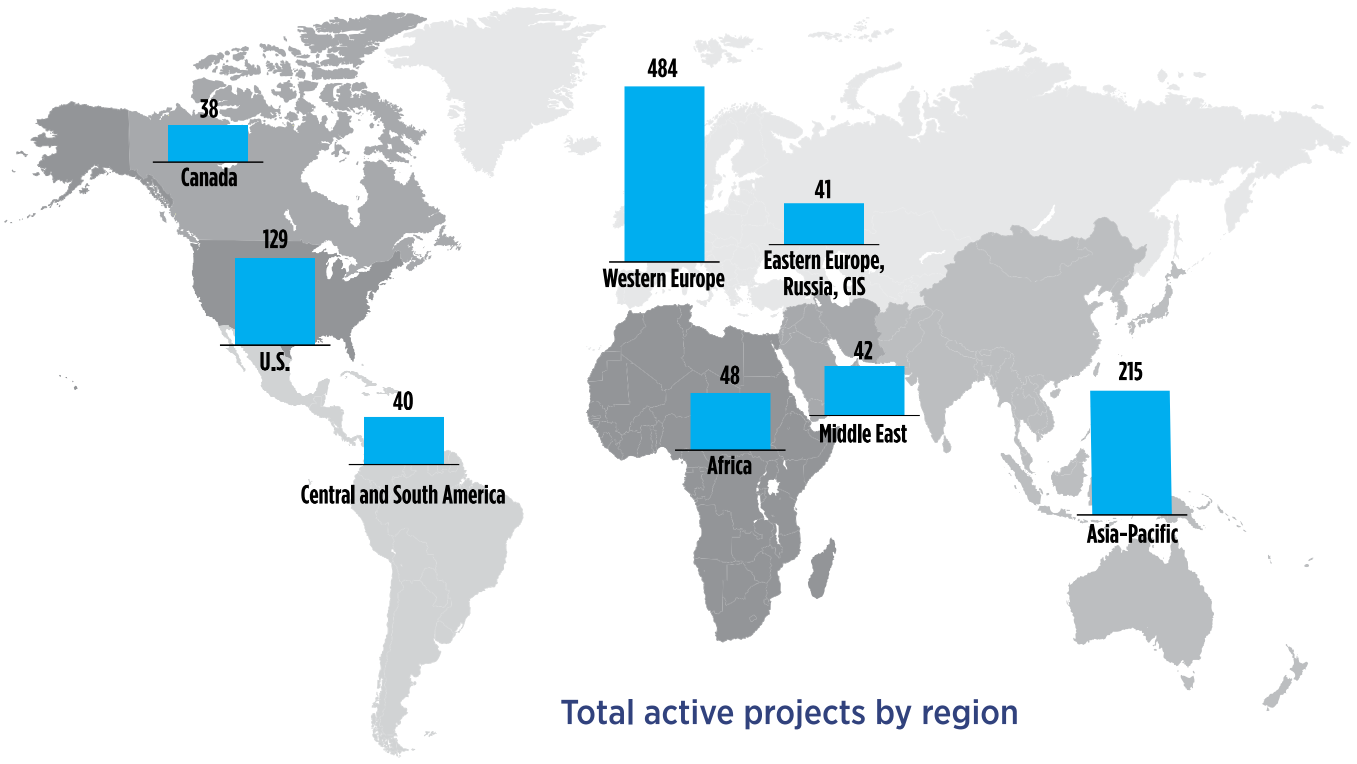
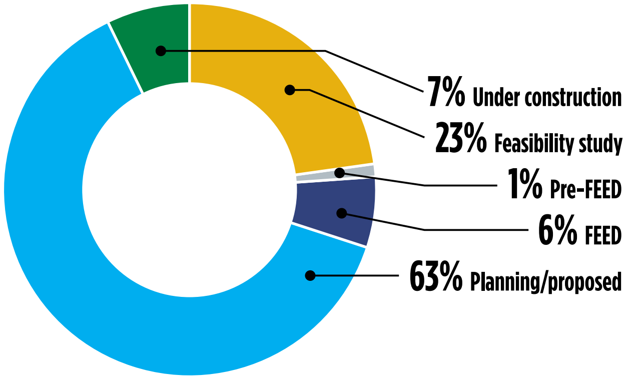
GLOBAL PROJECTS DATA

L. NICHOLS,
Vice President, Content/Editor-in-Chief

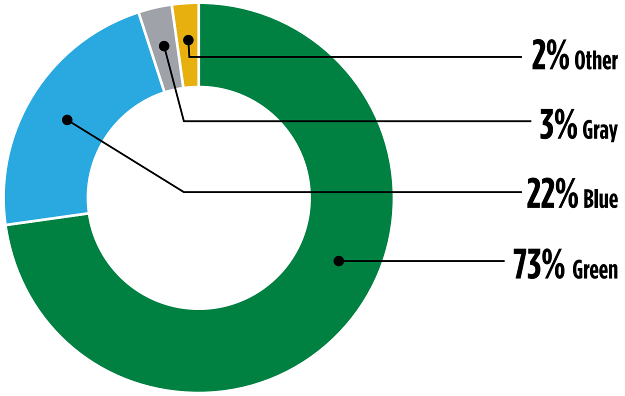
Gulf Energy Information's Global Energy Infrastructure database is tracking more than 1,030 active H_2 projects around the world. This is an increase of nearly 100 projects from data published in the Q2 issue. Most active projects are in Western Europe—the region holds a 47% market share. Western Europe is followed by the Asia-Pacific region, which accounts for 21% of active H_2 projects. Globally, nearly 75% of active H_2 projects are green H_2 developments, followed by blue H_2 projects (22%). Approximately 93% of active H_2 projects are in pre-construction phases.



Total active projects by region



Market share of active projects by status



Market share by type

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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

L. NICHOLS,
Vice President, Content/Editor-in-Chief

The H_2 Events Calendar keeps readers updated on H_2 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.

FEBRUARY 2023

American Hydrogen Forum
February 22–23
The Westin Galleria,
Houston, Texas
E: info@alj-group.com
www.ushydrogenforum.com

World Hydrogen MENA
February 27–March 2
Dubai, UAE
E: Oliver.Sawyer@
greenpowerglobal.com
P: +44 203-355-4208
www.worldhydrogenmena.com

MARCH 2023

World Electrolysis Congress
March 14–16
Düsseldorf, Germany
E: Oliver.Sawyer@
greenpowerglobal.com
P: +44 203-355-4208
www.worldelectrolysiscongress.com

MAY 2023

World Hydrogen North America
May 15–17
Houston, Texas (U.S.)
E: Oliver.Sawyer@
greenpowerglobal.com
P: +44 203-355-4208

Global Hydrogen & CCS Forum
May 24–25
Hamburg, Germany
E: info@alj-group.com
www.globalh2forum.com

JUNE 2023

First Element
June 12–16
Houston, Texas
FirstElementConf.com

Hydrogen Technology and Expo
June 28–29
NRG Center, Houston, Texas
E: Charlie.Brandon@
trans-globalevents.com
P: 404-737-8307
www.hydrogen-expo.com

SEPTEMBER 2023

Hydrogen Investment Forum
September 2023 (TBD)
PE Events
PEmedianetwork.com

OCTOBER 2023

World Hydrogen Congress
October 11–13
Rotterdam, Netherlands
Worldhydrogencongress.com
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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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