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MENA'S NEW ENERGY FRONTIER

CONTENTS

TO OUR INDUSTRY LEADERS

Countries across the MENA region are pushing ahead with ambitious plans to become major suppliers of low-carbon hydrogen and ammonia. Stay up to date with all the key trends and developments with *Hydrogen Economist*'s expert coverage.

Stuart Penson - editor

Stuart is the editor for *Hydrogen Economist* and *Carbon Economist* based in London. He has previously held senior editorial and management roles at Reuters, Dow Jones and Argus Media in a 30-year career covering energy, commodities and financial markets. He specialises in hydrogen and renewables, with a particular focus on traded markets and government policy.

Investment in large scale production of low-carbon hydrogen and ammonia is gathering pace across the MENA region as project developers in the region target emerging export markets in Asia and in Europe.

Saudi Arabia has taken an early lead with the $8.4b Neom project, which is on track to start producing 1.2mt/yr of green ammonia in 2026. Time will tell if Neom, which benefits from a long-term offtake arrangement with one of its main shareholders, is a template for future projects or a one off.

Other projects face challenges in securing offtake deals as potential consumers in key demand centres such as Japan remain reluctant to pay the green premium which many suppliers must charge to make their projects viable.

Despite these cost challenges, and broader uncertainty over future demand, developers are in deal-making mode. New projects and partnerships - spanning green and blue hydrogen, and ammonia - are advancing in Saudi Arabia, the UAE, Oman and elsewhere across the region. The UAE announced a flurry of deals in the wake of COP28, highlighting its ambitions to be a significant exporter.

In North Africa, international investors are flocking to renewables-rich Morocco, which is perfectly positioned to be a major supplier of green hydrogen into Europe. We hope you enjoy the following selection of articles by our global network of writers.

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ACWA EYES GREEN TRADE VIA AMSTERDAM

Saudi company signs MOU with infrastructure developers to explore plans for hydrogen export corridor via Dutch port

Saudi renewables developer Acwa Power is exploring the potential to ship liquefied green hydrogen to the Dutch port of Amsterdam as it steps up its efforts to build a hydrogen customer base in Europe.

It has signed a memorandum of understanding (MOU) with energy storage and distribution firm Zenith Energy Terminals, LNG shipping firm GasLog and the Port of Amsterdam to explore the potential creation of a "green hydrogen export corridor".

The MOU builds on a previous agreement signed between Saudi Arabia and the Netherlands on cooperation across a range of sectors including clean hydrogen; marine transport technologies, standards and certification; and the establishment of international supply chains connecting both countries.

"This collaboration is more than just a stepping stone—it is a leap towards a new horizon," said Marco Arcelli, CEO of Acwa Power. "As a first-mover in green hydrogen, Acwa is not just unlocking the potential of green hydrogen, the fuel of the future, but we are also exporting our expertise and commitment to a global audience. Our collaboration with GasLog, Zenith Energy Terminals, and the Port of Amsterdam signifies our dedication to clean energy leadership on an international stage."

> "This collaboration is more than just a stepping stone – it is a leap towards a new horizon" **Arcelli, Acwa**

Amsterdam is emerging as one of northwest Europe's hydrogen import gateways, along with Rotterdam and ports in northern Germany.

Acwa's MOU potentially gives it access to key hydrogen import infrastructure under development at Amsterdam, where Zenith is developing an open access liquid hydrogen import terminal. The facility will offer importers the option to regasify liquid hydrogen for delivery to the HyNetwork hydrogen pipeline system under development by Dutch gas network operator Gasunie. Importers could also export liquid hydrogen via barge and truck to offtakers including Amsterdam's Schiphol airport.

Zenith is also working with GasLog to develop specialised vessels capable of transporting liquid hydrogen.

Acwa aims to become a significant global supplier of green hydrogen. Its projects include the $8.5b Neom facility in Saudi Arabia. It is also a developing a green hydrogen project in Uzbekistan and is pursuing further projects and feasibility studies elsewhere in the Middle East as well as Africa and various other locations.

1–1.25MT/YR BY 2030 PRODUCTION TARGET

OMAN TURNS ATTENTION TO MIDSTREAM

Gulf state plans pipeline network and other infrastructure to support development of large-scale hydrogen production

As Oman prepares to receive proposals for integrated hydrogen projects under its latest bidding round, its attentions are turning to the infrastructure and regulation needed to support developers' plans.

In September, Oman's state-owned OQ Gas Networks (OQGN) signed a memorandum of understanding (MOU) with Belgian energy infrastructure company Fluxys to explore potential strategic collaboration on the development of the sultanate's hydrogen transportation infrastructure.

Separately, Hydrom, the government hydrogen company, included the installation of a 2,000km pipeline network in an outline of its wider plans to develop the common infrastructure required for the country's expanding slate of green hydrogen production, conversion and export projects.

Oman's national hydrogen strategy, published a year ago, calls for the sultanate to produce 1–1.25mt/yr by 2030. The IEA assessed in a report published in June that, based on the project pipeline, the sultanate would become the world's sixth-largest exporter of the fuel and its derivatives by that year—a huge fillip for Muscat's drive to make low-carbon hydrogen a bedrock of its economic diversification strategy.

Hydrom's first bid round, concluded in March, allocated land in the Duqm area on the central east coast to the developers of six schemes with a potential 700,000t/yr of combined green hydrogen output. It is also auctioning three 340–440km² plots in the southern Dhofar governorate under a second round, which is due to conclude by April 2024. Applications for prequalification are due by 8 October.

First round investors include BP, Shell and South Korean steel giant Posco. However, it is notable that none of the projects to which developers have provisionally committed have reached FID.

Lack of firm offtake deals required to make the schemes bankable is the central obstacle, but Muscat is also aware of the need for midstream infrastructure to smooth the path to construction and commissioning—and later to facilitate internal transfer of hydrogen to decarbonise domestic industry.

The attention to midstream development is running in parallel to the establishment of a solid legal and regulatory framework for the sector.

Pipelines

Speaking at an industry conference in London in mid-September, Hydrom Planning Manager Hafsa al-Subhi outlined the government's infrastructure plans. In the first phase, scheduled for completion by 2030, a common-user hydrogen pipeline network would be installed at the three emerging hydrogen clusters: Duqm, Al-Jazir and Salalah, with a link between Al Jazir and Duqm.

By 2040, Duqm and Salalah would also be connected, and a so-called 'hydrogen backbone' laid to transport the fuel to Sohar, Oman's main port and industrial city in the far north, where demand to decarbonise hard-to-abate industries such as steelmaking and cement will be greatest.

In the next decade, at the end of which production is due to have risen to 7.5–8.5mt/yr, the network would be expanded further, taking in Muscat.

While developers are responsible for installing the vast renewables capacity needed to power their projects' electrolysers, and the internal pipelines connecting the schemes' various upstream and downstream components, Hydrom will also construct other common infrastructure, including desalination plants and transmission lines, Subhi said.

The prospectus for OQGN's IPO—which aims to raise some $551m in the biggest share sale for over a decade on the Muscat Stock Exchange—also reflects the government's thinking around internal hydrogen transportation. It makes the case for dedicated pipelines, on the basis that adapting the existing 4,000km gas network to accept a blend of natural gas and hydrogen would be prohibitively costly at hydrogen levels of more than 10%. Another issue is the key customers, notably Oman LNG, require undiluted natural gas.

OQGN signed an MOU with Hydrom in June to collaborate on hydrogen pipeline development. The former's mandate to take the lead was confirmed by the tie-up with Fluxys, which is working domestically to develop a cross-country hydrogen pipeline in Belgium and an open-access green ammonia import terminal at port of Antwerp-Bruges. Most projects on Oman's slate call for converting the hydrogen to ammonia for export.

ELECTROLYZER TECHNOLOGY

Navigating the path to green H_2 for industry

As the "Swiss army knife" of decarbonization, "green" hydrogen (H_2) will have a huge role in reducing the carbon footprint in sectors where renewable energy and battery storage are not suited.

In the past, H_2 has not been cost effective as a fuel for industry or as an energy storage medium. However, this is changing rapidly, as several electrolysis technologies mature and compete to generate green H_2 using power from renewable energy sources. To move ahead in decarbonizing with H_2, companies must be familiar with these electrolysis options.

H_2 electrolysis terminology. Understanding the terminology is a good place to start. The language associated with H_2 electrolysis can be confusing, because any given term can be used in different ways in different contexts:

- *Electrolysis* is the electrochemical process of splitting a molecule of water (H_2O) into H_2 gas (H_2) and oxygen (O_2).
- An *electrolyzer* is the system that produces H_2 by means of electrolysis.
- A *cell* is a constituent element of an electrolyzer. Multiple cells are aggregated to comprise an electrolyzer (**FIG. 1**).

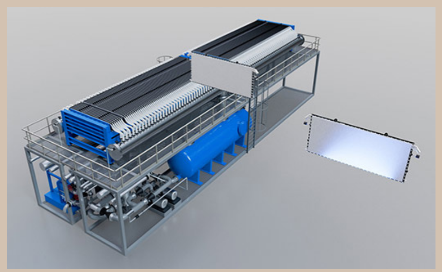


FIG. 1. Multiple cells are aggregated to comprise an electrolyzer.

- A *membrane* is one of the constituent elements of a cell. There are many different types of membranes, and their construction and operation are key to the fundamental differences between different types of cells and electrolyzers.
- *Levelized cost of energy (LCOE)* is an estimate of the lifetime cost of producing a form of energy and divides that by projected lifetime output. The result is a measure that essentially combines total cost of ownership (TCO) with return on investment (ROI).

TCO and ROI are already considered important measurements, so why use LCOE? Different energy technologies (e.g., wind, solar, natural gas, H_2) can be difficult to compare because power plants of different types can have vastly different capital costs, capacities, operating costs, life spans, risks and more. Because LCOE considers disparities, investors, analysts and policy makers can use this single measure to make reasonable comparisons of fundamentally different energy technologies.

The same calculation can be used to compare variants within a single energy technology category. The levelized cost of H_2 (LCOH) allows investors, analysts and policy makers to make reasonable comparisons of different H_2 production technologies.

H_2 production options. To date, essentially all industrial H_2 has been produced either from fossil fuels [e.g., via steam methane reforming (SMR)] or by energy derived from the burning of fossil fuels (e.g., via the chlor-alkali process). Both processes result in the release of significant amounts of carbon dioxide (CO_2), which contributes to global warming.

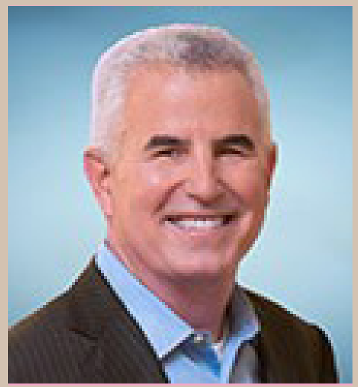
If a H_2 electrolysis plant uses power from a renewable source (green H_2), such as wind or solar, it will not produce or release CO_2. Electrolysis is an energy-intensive process, however. Until recently, the relatively high cost of renewable energy prevented the commercially viable production of green H_2.

With continuing reductions in the cost of solar and wind power, the price of renewable energy is now no longer a barrier. That said, now the *variability* of renewable energy production rates and pricing can inhibit investments in electrolytic H_2 production. The author's company has taken an approach that addresses this issue head-on—this is discussed in the following sections.

Cost-effective H_2 solutions must address three factors. The four major factors when calculating the cost-effectiveness of H_2 production (LCOH) are capital cost, output, efficiency and cost of energy.

Electrolytic cell companies commonly target only output and efficiency. Products have been designed that work at a specific current density (or a relatively narrow range of current densities) to produce a certain amount of H_2 and achieve a target level of efficiency.

While their technological achievements are undeniable, these other approaches are either too capital-intensive or they fail to account for fluctuations in energy production and pricing (the variables outside of anyone's control), or both.



M. NEESE, Verdagy, Moss Landing, California, U.S.

MARTY NEESE is the CEO of Verdagy, a green H_2 electrolyzer company that is seeking to fundamentally change the way industrial-scale H_2 is produced to massively decarbonize the most difficult sectors of our global economy. Neese's commitment to addressing climate change has been evident throughout his extensive career—he has spent the last 15 yr in the clean energy industry working to make solar, and now H_2, the least expensive, most economic and sustainable choice globally. He is a passionate advocate for the transition to a sustainable, circular economy with a goal of eliminating the concept of waste.

The ultimate goal is for H_2 production to connect exclusively to renewable sources. The problem is that the production of renewables is variable. The sun goes down at night; winds are not always constant.

It is entirely possible for a H_2 plant to operate connected to the grid. The advantage is that the energy supply would be steady. The disadvantage is the same as with renewables, however: pricing is unsteady. Energy prices rise and fall not monthly, weekly or even daily—the demand interval for energy is typically only 15 min, which means pricing can swing on a less-than-hourly basis.

Regardless of the energy source, if the output and efficiency of electrolytic cells are fixed, then even at improved levels their cost-effectiveness (if not their commercial viability) remains dependent entirely on energy prices remaining below a certain price threshold. Again, energy production and pricing fluctuations mean this is unrealistic.

Electrolysis and electrolyzers. Electrolyzers consist of an anode and a cathode with an electrolyte between them. Different types of electrolyzers function in different ways based largely on the cell design and the associated operating conditions and materials used for electrolysis.

The three main types of electrolyzers are:

- Polymer electrolyte membranes (PEMs), which are also referred to as a proton-exchange membrane
- Alkaline electrolyzers (AE), including alkaline-water electrolyzers (AWE)
- Solid oxide electrolysis cells (SEOC).

Combined, these commonly used descriptions are one of the biggest sources of confusion about the terminology associated with electrolytic production of H_2. One refers to a membrane, one to an electrolyzer and one to a cell. The terms appear to be interchangeable even though they are not.

Variations exist within each category of electrolyzer, including options to select different materials and chemical processes; of course, there are tradeoffs among them all. For example, SEOCs operate at very high temperatures [700°C–800°C (1,292°F–1,472°F)], while PEM electrolyzers and commercial alkaline electrolyzers typically operate near ≤ 100°C (≤ 212°F).

PEMs can change operating parameters relatively quickly, while AEs usually cannot. However, as noted, within each category there are variations.

The trade-off with PEMS involves the high cost of some materials—in particular, platinum group metals. Electrodes used in AEs do not require platinum-coated electrodes, and are consequently significantly less costly.

AWE electrolyzer technology. The advantages of AWE technology are compelling: material costs are lower, and it is possible to create significantly larger membranes operating at higher current densities. The author's company's novel advanced AWE cells[a] are among the largest in the industry, and can operate at 2A/cm², a current density that presently exceeds any other AWE technology. Bigger cells operating at higher current densities translates directly to more H_2 production per cell.

The author's company's patented advanced alkaline water electrolyzer is a type of alkaline electrolyzer; however, unlike previous AWE technologies, it can change operating parameters just like a PEM.

Equally important, the company's cell[a] and balance of plant are operable across a range from 0.1A/cm²–2A/cm², enabling a 20:1 turndown ratio. This dynamic range gives plant managers the flexibility to balance output and efficiency against energy availability, costs and H_2 demand. In particular, they can target production to the availability of renewable energy, thereby generating true green H_2. In general, they can ramp up production when energy is cheap or when demand for H_2 increases, and dial it back when prices rise. This capability is unique among available electrolytic technologies.

The author's company's architecture for a H_2 production plant has the ability to "gang" multiple electrolyzers (**FIG. 2**) to operate at 200MW, and to even scale up to gigawatt levels. Industrial plant operators can build out more top-end production capacity than demanded by the facility's nominal (faceplate) production rate target. They gain "extra" production (load gaining) when power prices are low, and reduced production (load shedding) when power prices are high.

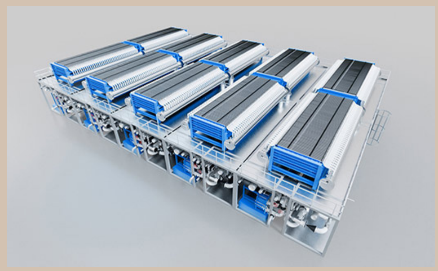


FIG. 2. The author's company's architecture for a H2 production plant has the ability to "gang" multiple electrolyzers.

This plant design takes full advantage of the wide dynamic range of cells[a]. Plant managers can change operating parameters within minutes to meet changing conditions, helping to optimize facility design and ongoing operating costs. The net result: a higher average production rate at a lower average energy price point without a dramatic increase in capital cost.

H_2 demand. In 2022, 99% of industrial H_2 was produced using a fossil fuel-based process, especially SMR. As the industry moves away from these processes, the market for green H_2 production will grow—It was estimated to reach $160 B in 2022 and is expected to grow to $263.5 B by 2027, according to MarketsandMarkets.

As more countries adopt decarbonization plans, H_2 will become widely useful. Initially, it will be best-suited where direct electrification is challenging and in harder-to-abate sectors like steel, chemicals, long-haul transport, shipping and aviation.

The near-term opportunity for heavy industry companies in areas such as steel and chemicals is to either use—or both produce and use—H_2 fuel. In this context, H_2 must be low carbon from the outset and ultimately green.

Other growth areas for H_2 fuel will be fuel cell electric vehicles (FCEVs) and for rockets used in the aerospace industry. There will also be increasing demand for fuel cells for bicycles, buses, trains, material handling equipment boats, ships, commercial aircraft, marine vessels and specialty vehicles such as forklifts.

LCOH will lead the way. All this growth depends on the LCOH of green H_2 decreasing rapidly. The author's company's advanced technology for electrolytic production of H_2 is designed to provide the lowest LCOH in the industry. By avoiding costly platinum group metals and leveraging the electrolyzer cell[a] size, current density and dynamic range, the company can achieve the lowest capital expenditure (CAPEX) in the industry and the lowest H_2 production costs when coupled with renewable energy.

NOTES

[a] Verdagy's eDynamic advanced AWE cells

The NGHC will undoubtedly serve as a model for other green hydrogen projects in the region

NEOM BLAZES GREEN HYDROGEN TRAIL

Neom Green Hydrogen Company's success may be difficult to repeat but provides important lessons – and similarities -- for future projects

The story of Neom Green Hydrogen Company (NGHC) may be unique but it is also one that should serve as a guide, perhaps a beacon, for other green hydrogen projects. The 2.2GW complex will produce both green hydrogen and ammonia in the planned Neom city in 2026 and will help drive Saudi Arabia's Vision 2030 sustainable development goals. But rather than be considered as a one-off, the initiative should be seen as a catalyst for growth especially across the Middle East which can funnel oil and gas wealth into other natural resources.

"The Middle East has all of the ingredients needed to make it a key region for green hydrogen development," said Alec Johnson, a partner in law firm White & Case's project development and finance group based in Riyadh, highlighting the region's abundant resources for wind and solar which are key inputs for power generation and large amounts of undeveloped land. The Middle East is well-placed for exports, given its proximity to the Suez Canal for European markets and existing shipping lanes to Asian markets.

"The challenge I think other investors have got is bringing a project to financial close. We did that with a 30-year offtake," Edmondson, NGHC

"There is an enormous amount of capital to be expended in the region given recent sky-high oil prices, both on the equity side with large sovereign wealth funds and other government related entities investing heavily in infrastructure projects, particularly those in non-traditional sectors," Johnson said. "Also on the debt side, given the maturity of the banking market here, particularly for projects that can be characterised as green and also the number of state-owned development funds that are active in the infrastructure sector," he added.

And this all plays out against a supportive policy framework that backs green hydrogen especially in the big oil producers such as Saudi Arabia and the UAE. But there is certainly an opportunity for coordinated government support across the Middle East for green hydrogen in the form of investment incentives or regulatory changes. After all, the region is a hot bed for hydrogen derived from fossil fuels which has been a focus as well.

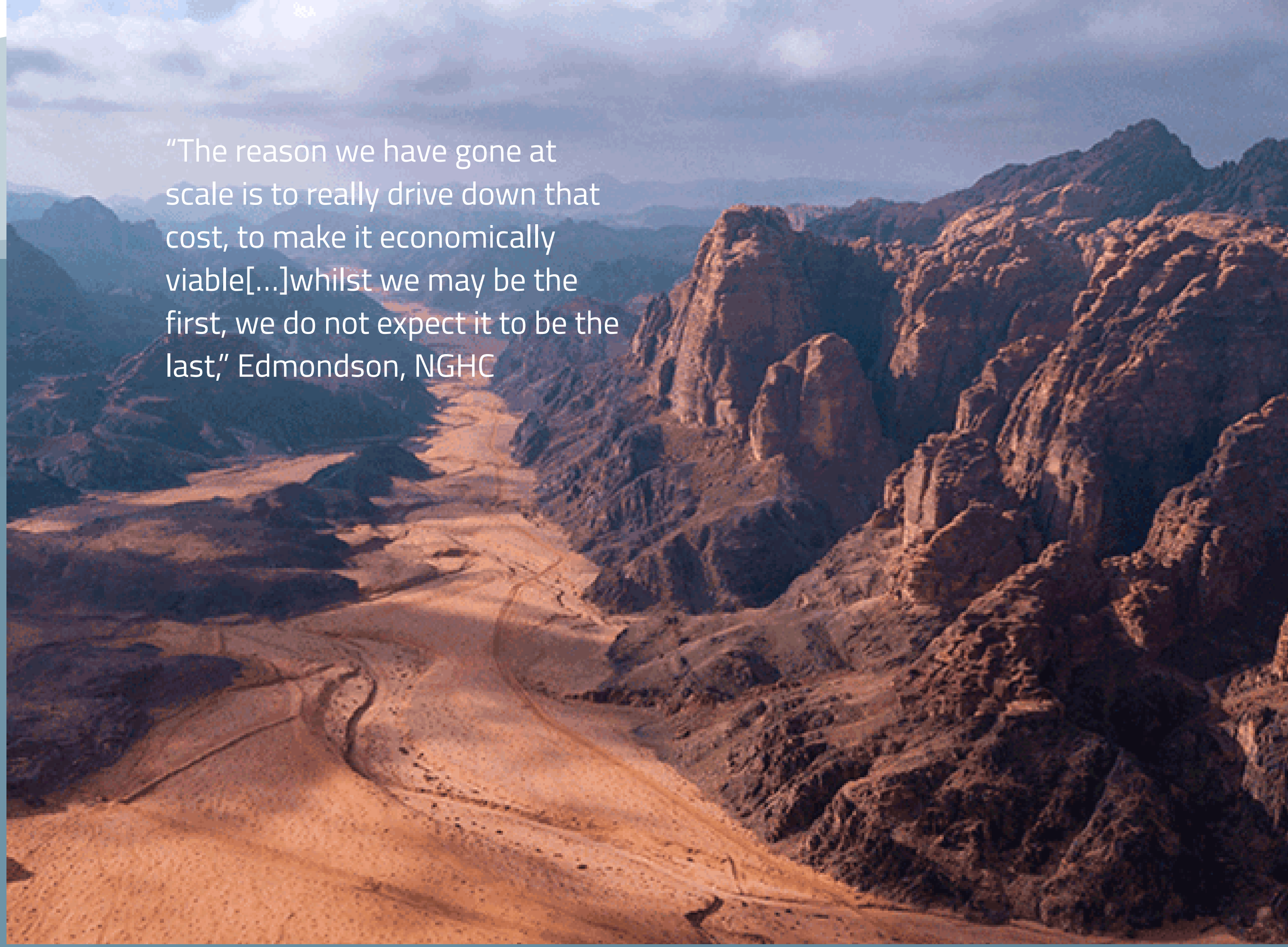
David Edmondson, CEO of the NGHC told Petroleum Economist about Saudi Arabia's commitment, their desire to be one of the leading energy exporters by 2030, and that some bold commitments around Vision 2030 were a key driver.

"When the three shareholders – Neom, Saudi renewables developer Acwa Power and industrial gases distributor Air Products – came together, back in 2019, they agreed they wanted to build a world class green hydrogen facility[…] At the time, green hydrogen was not really talked about in the public, but there was a commitment from the chairmen of the three companies," Edmondson explained. "They believed they could make this happen and they believed that the market would come. And that was fairly visionary at the time," he added.

The project is likely to produce up to 600t/d of green hydrogen from 110 20MW alkaline electrolysers powered by 4GW of wind and solar. Some 1.2mt/yr of ammonia will eventually be exported.

Edmondson also points out that size really does matter. "The reason we have gone at scale is to really drive down that cost, to make it economically viable," he said, adding "whilst we may be the first, we do not expect it to be the last."

The CEO explained that "we have actually opened a lot of doors for other businesses and other companies to look at these investment opportunities" given that with investment it has shown that "this business proposition is absolutely viable and we have proved it with a 30-year offtake".



Carina Radford, a partner in White & Case's energy infrastructure and project finance group, points out that the "finance appetite was clearly there" and that while the scale was unique and there was innovation within its commercial structure and operations, it was about rooting it in the familiar and highlighting that the individual parts such as solar and wind farms or ammonia production had experienced players attached who knew the risks.

"We tried to undo some of the scary headline aspects of this and lean into some of the things that the financiers recognised, some of the risk allocations that they have seen across many of these projects before and hold their hand as much as possible through the technical and commercial story," Radford said.

Edmondson said that "one of the things that made it so compelling was the offtake agreement." And again, if you look at the shareholders, there is so much synergy between them and so much experience in their fields of expertise, Edmondson underlined.

Edmondson said that Air Products were willing to commit to take all of the product at a price and for a duration that they believed would enable them to supply the market long term. And that was at a time when there really was no market for green hydrogen. Even now there is no real understanding about market pricing on green hydrogen, Edmondson explained.

With a total investment of $8.4b, the project has reached financial close. "The challenge I think other investors have got is bringing a project to financial close. We did that with a 30-year offtake," said Edmondson, underscoring the great leap that was made.

Clearly the importance is on creating both supply and demand. "So policy and incentives obviously need to be focused both on production but also on the customer side," Radford said.

"How do you incentivise the uptake of hydrogen as a fuel in various industries and at the same time incentivise people to make some large capex investments in the supply side so that they come together gloriously at one moment, a kind of field of dreams. Kevin Costner moment?" The demand has to be there, was the answer.

Edmondson also talked up the importance of collaboration. "To have reached financial close in the time that we did, considering where we started was huge[…]everyone had to play their part because without that we could have come undone at any moment in time."

The NGHC will undoubtedly serve as a model for other green hydrogen projects in the region. Some of these projects might look a lot like Neom and the offtake agreement will be key even if they will not be as fully integrated.

What is clear is that Neom will serve as the benchmark for all new green hydrogen projects in the region.

52% | 2030 TARGET RENEWABLES SHARE

MOROCCO RIDES WAVE OF GREEN HYDROGEN INTEREST

International investors are looking to exploit Morocco's increasingly well-recognised potential to be one of the world's top producers

French developer HDF Energy in November announced plans to develop a multi-gigawatt green hydrogen project on Morocco's southwest coast—delivering the latest international vote of confidence in the country's prospects in the sector.

The north African kingdom—which has ideal climactic conditions and plentiful available land—is emerging as a hotspot for low-cost production and exports.

The International Renewable Energy Agency believes Morocco could be the third lowest-cost producer of hydrogen by 2050 (at $0.7–1.4/kg), capturing around 4% of international export demand.

A recent study by UK-based consultancy Deloitte foresees North Africa becoming one of the two leading locations, alongside Australia, for production and exports of hydrogen and its derivatives by mid-century.

The HDF scheme—dubbed White Dunes and to be developed in partnership with the local firm Falcon Capital—covers the phased construction, starting in 2025, of an 8GW plant in the far southern Dakhla-Oued Ed-Dahab region. The project would be based on 10GW of wind and 7GW of solar power, with first hydrogen production scheduled for 2028.

The Bordeaux-based firm has been working for two years with local fuel storage joint venture Somas on a project to convert salt caverns on the Casablanca-Rabat axis for hydrogen storage.

Other developers are also lining up significant projects. In May, US-based CWP Global signed a memorandum of understanding with Germany's Hydrogenious LOHC Technologies to conduct a feasibility study into exporting 500t/d of hydrogen from the former's planned 15GW Amun green hydrogen plant in the southwestern Guelmim-Oued Noun region to Europe using the Bavaria-based firm's liquid organic hydrogen carrier (LOHC) technology, an alternative to converting the output to ammonia or bunkering fuels. CWP has completed the feasibility on the 7GW first phase of the proposed Amun plant, due onstream in 2029, and the pre-feasibility study on the second, slated for startup in the early 2030s.

Earlier this year, Belgian engineering firm John Cockerill unveiled plans to establish an alkaline electrolyser gigafactory in Morocco, a project touted as the first of its kind in Africa.

L'Offre Maroc

The government is working hard to bolster the country's allure to investors. It intends to unveil shortly 'L'Offre Maroc'—an investment framework for prospective green hydrogen developers covering issues such as land allocation, respective responsibilities for infrastructure development and relationships with relevant government agencies.

The provisions will build on those enshrined two years ago in the Investment Charter, which offers state financial support of up to 30% of capital costs for projects in priority sectors, including clean energy, while also providing for the extension of tailored incentives for schemes worth over MAD2b ($198m) and deemed 'strategic' by dint of their potential impact on employment and energy security as well as their international economic influence.

Forced to import over 90% of its fossil-fuel requirements, Rabat has already moved faster and further than its neighbours in developing its ample solar and wind resources—with renewables capacity of 3.7GW accounting for 38pc of the power mix by the end of 2022 and targeted to reach 52% by 2030.

A massive scale-up—to well over 100GW by 2050—would be required to meet the state's green hydrogen ambitions but the resources are there given Morocco's 2,500km coastline and the fact that 80% of land comprises sparsely populated near-desert. A World Bank Study published in 2020 placed Morocco in the top 20 potential solar PV producers globally, positioning it as a future green hydrogen powerhouse.

CONVERTING EXISTING INFRASTRUCTURE

Sustainable ports: Learnings from an Omani ports research study

The ongoing energy transition is shaping a new world that will ultimately be powered by emissions-free energy. Of the impending transformations, the global supply chain—today, largely based on fossil fuels—is set to undergo fundamental changes in transport and infrastructure. The hydrogen (H_2) and derivative transport markets are expected to reach up to 400 MMtpy by 2050,[1] representing an excellent opportunity for ports to become central and active hubs for logistics, manufacturing and other industrial activities. Localizing new business activities in and around ports can deliver in-country value by stimulating regional and national growth and creating new job opportunities.

The author's company recently conducted a study on behalf of ASYAD and in cooperation with the Oman Hydrogen Centre.[2] The report analyses in depth the three main deep-sea Omani ports and related opportunities, providing lessons that can be applied to ports worldwide in the context of the energy transition.

Ports as H_2 valleys and clean H_2 hubs. H_2 valleys are envisaged as integrated ecosystems that cover the entire spectrum of value chain elements, from production to final consumption. All activities—zero- and low-emissions H_2 production, storage, distribution and use—are meant to be concentrated in a specific geographic area, resulting in benefits such as lower H_2 costs, enhanced investment attraction and industrial localization. Therefore, ports are ideal locations to become H_2 valleys and fully-fledged clean industrial hubs, provided integrated activities are planned early in the process and leverage existing assets and industries.

Ports would provide a great stimulus in accelerating decarbonization efforts for existing plants (e.g., refineries and steel assets already located at ports or in the vicinity). Early adoption of H_2 can lower emissions and provide an important competitive advantage as the demand for clean products will soon be predominant.

Attracting new industries—especially those that are energy-intensive—directly impacts local economies and contributes to in-country value creation. Existing supply chains (e.g., dry docks, welding capabilities) can be extended wherever possible to cover the H_2 space. Localizing new production facilities in or at nearby ports helps reduce H_2 transport and derivatives costs. Equally important is designing an efficient infrastructure system based on repurposing existing facilities or completely new networks, depending on each country's needs and regulatory requirements.

As high emitters of carbon dioxide (CO_2), ports are well-positioned to coordinate all CO_2 capture initiatives nearby. CO_2 could then be stored temporarily before usage, injection, sequestration or export. Besides storing CO_2, ports offer storage opportunities for different products (e.g., the bunkering of H_2 derivatives) to all industries in the valley that can be complemented by underground storage in suitable, nearby locations.

While the first H_2 valleys are nascent, it is important to note that some are planned around ports (e.g., the Port of Rotterdam) or connect multiple ports (e.g., the Ports of Flanders, including the Port of Antwerp-Bruges, North Sea Port and Port Oostende). Collaborations and learnings from these early experiences can stimulate similar plans on other continents. Additionally, building close cooperations with global associations like the Global Maritime Forum (GMF) can facilitate connections to the broader value chain.

Potential application for H_2 at the ports. Ports are in a favorable position to lead the adoption of H_2 to decarbonize operations and logistics, thus optimizing their energy efficiency and carbon footprint (**FIG. 1**). For the three Omani deep-sea ports, several potential applications have been identified, most of which can be replicated elsewhere:

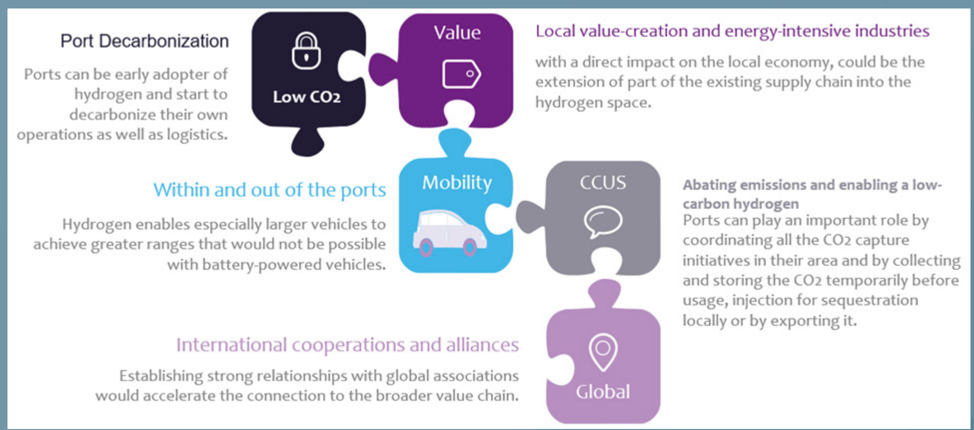


FIG. 1. Potential operations and logistics to be decarbonized with H_2.

- **Logistics.** Internal logistics and mobility within and out of the ports can benefit from deploying H_2-powered vehicles (e.g., trucks, forklifts). Solutions to reduce carbon footprint are already available in other sectors (e.g., H_2 mobility projects at airports) and can be easily applied to ports. Furthermore, low-carbon cold chain logistics development can leverage advancements in fuel cell technology for high energy-consuming vehicles like refrigerator trucks.
- **Bunkering.** Ports in strategic locations can aspire to become low-emissions bunkering hubs, taking advantage of the H_2 derivatives trade flow's evolving landscape. It is advisable for neighboring ports to coordinate their efforts and differentiate the offering of bunkered products to avoid competing in the same market.
- **Ship refueling.** With the ongoing efforts to decarbonize shipping traffic, H_2 derivatives (e.g., ammonia, eMethanol) are expected to gradually replace fossil fuels. The evolution of ocean vessel engines represents an important opportunity for ports to refuel ships with low-emissions ammonia and eMethanol during the unloading and loading of goods.
- **Heavy industry.** Ports usually host heavy industries, such as steel and cement production. However, ammonia and methanol production requires large amounts of energy. Gradually replacing fossil fuels with H_2 is an important opportunity to reduce carbon emissions and decarbonize industrial processes.
- **Refineries.** Many refineries are located in or near ports, producing and consuming significant H_2 for crude oil desulfurization. As a first step, H_2-based fuels can be blended with conventional fuels to satisfy the increasing quota of sustainable fuels required by certain industries (e.g., aviation). In this context, refineries can become enablers of clean mobility, keeping in mind that, ultimately, traditional refineries will cease to exist and will fully convert into eFuels production sites.

Shipping pathway to decarbonization. The shipping industry is responsible for 3% of global CO_2 emissions—this will require important transformations in the coming years. Major operators worldwide are implementing strategies to drastically reduce carbon emissions, mostly based on adopting eFuels to meet their decarbonization targets. However, the GMF warns that targets should be supported by regulations and policies to close the gap price with fossil fuels and drive the demand for low-emissions eFuels.[3] Some international regulations are already in place, such as the International Maritime Organization (IMO) requirements and European Union regulations.[4] Additional standards are in development (e.g., Carbon Border Adjustment Mechanism).[5] Shipping operators and ports should account for these rules, especially when exporting goods across different countries.

The demand for dual-fuel engines is rising and expected to increase to 50% by 2032 at a marginal cost of only 10%–20% higher than traditional engines. Regarding eFuels, ammonia and eMethanol are projected to reach comparable demand by 2030 and compete with liquified natural gas (LNG) for an equal market split.[6] It is worth noting that, besides its use as shipping fuel, ammonia is likely to be the carrier of choice for sea transport.

Takeaway. Ports have the potential to play a crucial role in the ongoing energy transition by developing into H_2 valleys and clean industrial hubs. Such clusters could serve as catalysts for developing H_2 value chains, thus attracting new businesses and creating new job opportunities. Localized H_2 use and processing can decarbonize port operations and reduce their carbon footprint. Several potential applications for H_2 and derivatives at ports have been identified, such as decarbonizing logistics, heavy industry and refineries, as well as bunkering and ship refueling. Existing assets can benefit greatly from the early adoption of H_2 in decarbonization efforts and gaining a competitive advantage as demand for low-carbon products constantly increases. H_2 and derivatives will be key in facilitating decarbonization in the shipping sector. Ammonia and eMethanol are forecast to soon compete with heavy fuels in the shipping sector, provided regulations and policies are in place to help drive clean fuel demand.

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SPECIAL FOCUS:
MAINTENANCE AND RELIABILITY

How high-performance fluid systems help maximize H_2 electrolyzer production

As the world moves toward a low-carbon energy future, the race for viable fossil fuel alternatives continues, with hydrogen (H_2) having significant potential to revolutionize energy. Multiple analysts forecast it will continue its exponential growth as countries worldwide discover how well H_2 produced through electrolysis works. The questions surrounding its long-term viability focus on how easily it can be produced and how much global capacity will exist.

Ensuring reliable H_2 production begins with the centerpiece technology of the production process: optimized electrolyzers (**FIG. 1**). Typically, production facilities can use one of two primary configurations of their electrolyzers [e.g., alkaline and proton exchange membrane (PEM) electrolyzers] to convert water and electricity into H_2 and oxygen. Efficient, effective conversion depends on the electrolyzer's reliable water delivery and functional outflow of the resultant gases.

FIG. 1. Optimizing your electrolyzers is the first crucial step toward building and maintaining an effective, efficient production facility.

As engineers design H_2 production facilities, they must focus on creating well-constructed fluid systems to ensure peak performance of the plant (**FIG. 2**). In fact, effective fluid systems can significantly influence the safety, productivity and profitability of H_2 production facilities.

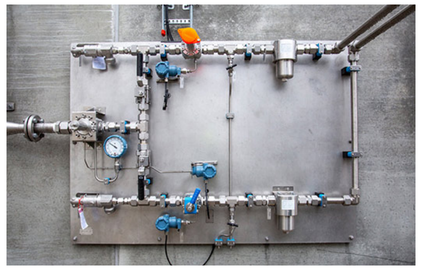

FIG. 2. The fluid systems that supply water to the electrolyzer and capture the resultant H2 and oxygen gases are central to determining how well an electrolyzer will function.

Avoiding leaks as the system is installed. The best way to ensure proper fluid system performance is to meticulously design, install and test the systems as the facility is being built. During the final stages of a H_2 production facility build, engineers frequently test the crucial fluid systems using factory acceptance testing (FAT) standards. Not only are major components inspected and qualified at the supplier's site, but the entire system is also often tested by pumping a benign test fluid, such as helium or a mixture of helium and nitrogen, through the tubes at ever-higher pressures to ensure no leaks are present.

Electrolyzer performance is often dependent on leak-free fluid systems keeping the water flowing at adequate levels, and leaks at the end of the process—when H_2 and oxygen are captured—may lead to product losses and potentially put employees at risk with an unexpected safety hazard. In addition, other fluids, such as liquid alkaline solutions, may be present in the system, and it is crucial for the reliability of the process and the safety of the operators to have these lines leak free.

If any leaks are detected during FAT:

- The testing process must be shutdown
- The system must be purged of the test gas
- Operators must identify the leak points
- The leaks must be repaired via manual intervention in the system
- The testing must be restarted from the beginning.

Improper installation techniques are the most common reasons leaks exist in fluid systems. Since all leaks must be repaired, they create unnecessary downtime as they are fixed, leading to lower production levels and diminished profitability. Therefore, it is essential to eliminate leaks from the beginning so all new H_2 production facilities can succeed.

To prevent leaks during construction, it may make sense to take advantage of any installation training suppliers can provide (**FIG. 3**). Proper training can help facilities reduce costs during startup. The supplier should also be able to advise on installation best practices, so start-up delays and expensive redesigning of crucial fluid systems can be avoided. Well-trained installers are less likely to make common mistakes that can lead to a system developing leaks at its connection points.

FIG. 3. The best installation practices include using a gap inspection tool to verify fittings are tightened properly.

Keeping your H_2 output clean. Properly functioning electrolyzers should produce H_2 that reaches 99.9% purity if it is to be used as a fuel source for other equipment. Keeping that purity level depends as much on the outflow fluid systems as on the electrolyzer.

The key to maintaining this purity in the post-electrolysis fluid systems is using the highest-quality components possible. The electrolysis process significantly raises temperatures and humidity near the tubing systems, which can damage lesser-quality stainless steel components. In turn, fluid system corrosion can lead to the contamination of the end products (**FIG. 4**). Damage like corrosion also poses a potential safety hazard because corroded containers are more likely to fail.

FIG. 4. If collection systems corrode due to high heat and humidity, they can inadvertently contaminate the end product, which can slow production and lead to downtime while the corroded equipment is replaced.

Fortunately, there are several methods operators can use to keep their H_2 purity high, including close monitoring of the end products using high-quality gas grab sampling systems or via online monitoring of the quality through an effectively designed system. In addition, the material makeup of the collection containers is critical. To ensure containers are less likely to corrode or suffer from H_2 embrittlement, components in these systems should be made of high-quality stainless steels with higher concentrations of chromium and nickel than The American Society for Testing and Materials (ASTM) requires (**FIG. 5**).

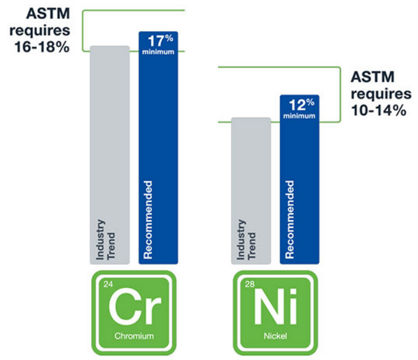

FIG. 5. High-quality components that contain higher levels of chromium and nickel will more readily resist corrosion and H_2 embrittlement.

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Making sure the facility is as productive as possible. Since the production of H_2 as a fuel is growing and evolving, no one knows for certain how to bring a new plant online with guaranteed reliability and cost-effectiveness. Part of what is understood by most facility operators is that adequately executed H_2 production requires proper fluid transfer. For this reason, best practices learned from many years of expertise in handling fluid systems can help reduce leaks, safety challenges and maintenance issues in H_2 production facilities. Well-managed fuel systems at the ingress and egress of the H_2 systems enable electrolyzers to be used to their full capacity. That allows facilities to produce H_2 efficiently to meet demand (**FIG. 6**).

FIG. 6. Keeping the supporting fluid systems maintained properly will help a H_2 process facility keep up with the ever-increasing demand for H_2.

Fewer connection points at the design stage and leak-tightness at the installation phase prevent potentially expensive reconfigurations during FAT and may reduce the number of maintenance issues and related downtime that must be addressed over a system's lifetime. Reliable inflows and clean outflows allow the process to be as efficient as possible, which can keep the total ownership cost manageable over the production facility's life. Maintaining proper inflows and outflows is another reason operators should pay close attention to the fluid systems supporting the electrolyzer's function.

The key to operating a successful H_2 processing facility is to choose high-quality components and assemblies from the beginning. They should be explicitly designed to handle H_2 safely and effectively. Preparing for H_2 production from the beginning will enable the facility to get up and running more quickly, safely and productively. In this increasingly competitive green H_2 market, speed and precision are critical. A reputable supplier should be able to provide the guidance necessary to ensure the right components are in place to make the operator's facility a success.

What are the two most prevalent electrolyzer designs? Choosing the right electrolyzer for your facility will depend on which one makes the most sense for your application (**FIG. 7**). For H_2 production, you have a choice between two main designs:

- **Alkaline electrolysis (AEL) electrolyzers.** AEL electrolyzers use alkaline electrolysis, a mature technology that has been used for more than 100 yr. Alkaline electrolysis uses a liquid alkaline solution of potassium hydroxide or sodium hydroxide as an electrolyte to conduct electricity, operating at low temperatures. It splits water into H_2 and oxygen using this electrical current. It is the cheapest form of H_2 production but comes with high maintenance costs.
- **PEM electrolyzers.** PEM electrolyzers use a solid electrolyte rather than a liquid form to conduct electricity. PEM electrolyzers are more efficient, require less maintenance and take up a smaller footprint than their AEL counterparts. However, PEM electrolyzers are more expensive to operate, as they require precious metals like platinum.

Regardless of which electrolyzer technology is used, the fluid systems that feed and collect the finished H_2 are critical to ensuring the electrolyzer always operates at peak performance.

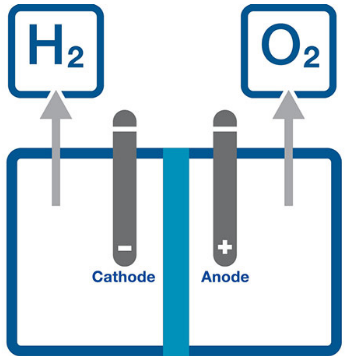

FIG. 7. A H_2 electrolyzer separates water into H2 and oxygen molecules using electricity.

Buyers in Asia reluctant to commit despite Saudi state firm being one of the lowest-cost producers

ECONOMICS OF CLEAN HYDROGEN AND AMMONIA 'VERY CHALLENGED' — ARAMCO

Aramco is seeking hydrogen buyers

The economics of low-carbon hydrogen and ammonia are "very, very challenged" and the industry is grappling with difficult questions over the role of policy and the ability to pass costs on to end-users, Jean-Paul Desrochers, manager of low-carbon hydrogen at state firm Saudi Aramco, told the World Hydrogen Congress in Rotterdam.

Even as one of the lowest-cost producers of blue hydrogen, ammonia and green hydrogen, Aramco is encountering reluctance among potential offtakers in Asia because of the price, he said. The firm is in talks with potential buyers in Japan and South Korea, which are bringing in regulations and incentives to try to drive use of ammonia in the power sector.

"Without those incentives, we are hearing from the market that it is difficult for them to contract," Desrochers said. "As a producer, we think we can produce some of the lowest-cost blue ammonia and blue hydrogen, as well green hydrogen, but even with the lowest costs of these products, the end-user is still struggling with committing to buy."

Power utilities are risk-averse when it comes to the switch to hydrogen, the costs of which would need to be passed on to end-consumers in the form of higher electricity rates, he added.

Desrochers said he favoured the use of incentives rather than legislation mandating the use of low-carbon products but ultimately a combination of both will probably be needed to bridge the gap between the value of the green product and the willingness of consumers to pay.

Aramco aims to start supplying low-carbon hydrogen and ammonia to the market in 2027 at a rate of c.1.5mt/yr before ramping up production towards the end of the decade.

"We have big plans to expand by 2029," Desrochers added.

Global market

A global market for low-carbon hydrogen will ultimately emerge, but there is unlikely to be a single unified price, he said. Prices will reflect different regional dynamics through differentials, as with other commodity markets such as LNG. But hydrogen and ammonia pricing would be more complex than other commodities because of the various inputs including renewables and—in the case of ammonia—differing sources of hydrogen.

Pricing for ammonia for use in energy applications will be further complicated by the fact that there is already a market in some sectors such as fertiliser.

"Pricing for hydrogen is going to be much more complex, with a lot more factors influencing it than, for example, the LNG market," Desrochers said. "It is going to take time for that market to evolve because right now there is no hydrogen market, there is no ammonia market as it relates to energy. And that is a challenge—buyers want price stability, but how do you price your product for 10–15 years if there is not a market?"

Power utilities are risk-averse when it comes to the switch to hydrogen

BUSINESS TRENDS

The future of H_2: A regional outlook—Part 3: The Middle East and U.S.

Nations around the world are investing in new technologies and pathways to limit carbon emissions and adhere to ambitious net-zero goals. Part of this strategy includes the massive scale-up of hydrogen (H_2) production capacity, primarily green routes that use renewable energy for production.

Part 1 of this work—published in the June issue of *H2Tech*—detailed current and future H_2 demand, active H_2 project numbers and capital spending globally, as well as an examination of major H_2 trends, programs, regulations and capital projects in Africa, Asia and Canada. Part 2—published in the July issue of *H2Tech*—focused on Western and Eastern Europe, Russia, the Commonwealth of Independent States (CIS), and Central and South America. This final article will examine major H_2 developments in the Middle East and the U.S.

MIDDLE EAST

With abundant solar and wind energy potential, the Middle East is keen on developing its renewable energy generation and H_2 production potential. According to the Gulf Petrochemicals and Chemicals Association (GPCA), the Gulf Cooperation Council's (GCC's) H_2 market could experience a compound annual growth rate (CAGR) of 15% between 2022 and 2050, resulting in potential revenues of $120 B/yr–$200 B/yr.[30]

However, achieving this forecasted growth will require significant capital expenditures (CAPEX) in renewable energy capacity, infrastructure, electrolyzer development and installation, and H_2 deployment in various industries within the region. According to the MENA Hydrogen Alliance's "The Potential for Green Hydrogen in the GCC Region" report, installing renewable and electrolysis capacities would require $16 B/yr–$60 B/yr over the next 25 yr, with approximately 30%–40% attributed to renewable energy capacity—The Middle East's renewable energy capacity reached 40 GW in 2020 and is expected to double by the mid-2020s.[31,32]

Active projects. Regardless of the costs, the Middle East is investing heavily in developing its H_2 value chain, including contracts to export green and blue H_2 to demand markets in regions such as Western Europe. At the time of this publication, Gulf Energy Information's Global Energy Infrastructure (GEI) database was tracking nearly 50 active H_2 projects in the Middle East. These projects represent a total CAPEX of more than $200 B.

According to the GEI database, most projects are in Oman (36%), followed by the United Arab Emirates (33%) and Saudi Arabia (15%). Although Saudi Arabia ranks third in active H_2 projects in the Middle East, the country represents more than half of the total CAPEX in the region. Nearly 70% of active H_2 projects in the Middle East are through green production pathways, followed by blue routes (22%). A breakdown of total active H_2 project market share in the Middle East by country is shown in **FIG. 11.**

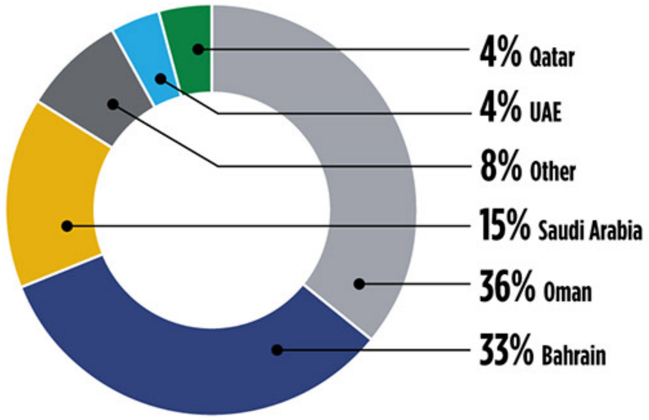

FIG. 11. Active H_2 project market share in the Middle East. Source: GEI database.

Oman. The country has ambitious goals of producing approximately 1.25 MMtpy of green H_2 by 2030, increasing production to 3.75 MMtpy by 2040 and up to 8.5 MMtpy by 2050. This initiative will cost upwards of $140 B to become a reality, according to Oman's Ministry of Energy and Minerals' *Green Hydrogen Strategy*.[33] A significant portion of this CAPEX will be for the scale-up of renewables capacity. According to *Oman Vision 2040*, the country is targeting the ramp-up of renewables capacity market share in the country's energy mix from 1% today to 20% by 2030 and up to 35%–39% by 2040.[34]

The nation plans to develop green H_2 in three regions: Al Wusta, Dhofar and Duqm. These development plans will be instituted in a phased approach. Phase 1 includes the Al Wusta and Dhofar regions—the Omani government has set aside more than 50,000 km^2 for renewable energy and green H_2 project development in these areas.

In June, Oman awarded three renewable energy and green H_2 production projects totaling $20 B. These projects will increase Oman's renewable energy capacity by 12 GW and green H_2 production by 500,000 tpy:

- Copenhagen Infrastructure Partners, Blue Power Partners and Al Kadra are building 4.5 GW of renewable energy to help produce 200,000 tpy of green H_2.
- bp Oman will install 3.5 GW of renewable capacity to produce 150,000 tpy of green H_2. The green H_2 will be used for ammonia production and exported to international demand centers.
- Green Energy Oman plans to build 4 GW of renewable capacity to produce 150,000 tpy of green H_2.

These projects will be complemented by other major green H_2/ammonia projects, including the large-scale HYPORT project, which will produce nearly 3 GW of renewable energy and more than 650,000 tpy of green ammonia; ACWA Power, Air Products and OQ's multi-billion-dollar H2Oman project; ACME and Scatec's 1.1-MMtpy green ammonia project; the Hydrogen Oman and Salalah Hydrogen projects in the Salalah Free Zone; Hydrom's $7-B–$8-B green H_2/ammonia project in Duqm, which will produce 220,000 tpy of green H_2 and 1.2 MMtpy of green ammonia; and other green H_2 production plants, infrastructure (e.g., pipelines) and export facilities.

Saudi Arabia. The Kingdom has ambitious plans to be a dominant player in low-/zero-carbon H_2 production and in global H_2 trade, all the while striving for a net-zero economy by 2060—this green initiative is expected to cost upwards of nearly $190 B. Saudi Arabia is making great strides to incorporate more renewable energy capacity into its energy mix. According to the *Saudi Green Initiative*, Saudi Arabia plans to boost its renewables' market share in the country's power generation mix to at least 50% by the end of the decade. The additional renewable energy will aid the country in meeting its H_2 production targets of 2.9 MMtpy by 2030 and 4 MMtpy by 2035.[35]

The nation's most ambitious initiative is the $500-B NEOM project. As part of Saudi Arabia's *Vision 2030*, NEOM is a city being built on the Red Sea that will run entirely off renewables. NEOM Green Hydrogen Co. is developing a world-scale green H_2 production facility to provide power to parts of the city and transportation network. The $8.4-B plant will utilize solar power from a nearby 4-GW solar farm to produce 600 tpd of green H_2. The produced green H_2 will not only be used to provide power to the city's industry, but will also be utilized to fuel buses and trucks.

Saudi Arabia also plans to tap into its vast natural gas reserves to increase blue H_2/ammonia production. For example, Saudi Aramco, the nation's national oil and gas company, announced plans to boost blue ammonia production to 11 MMtpy by 2030. To help achieve this goal, the country is developing the $110-B Jafurah unconventional gas project. The project's initial phase—production is scheduled to begin in 2024—will process more than 1.1 Bft^3d of natural gas, increasing significantly to more than 2.2 Bft^3d by 2036.[36] Portions of Jafurah's natural gas will be used to produce blue H_2. However, due to the high costs of producing blue H_2, Saudi Aramco is evaluating using the gas for LNG exports should the company be unable to find suitable customers for blue H_2/ammonia.

United Arab Emirates (UAE). Like other countries around the world, the UAE plans to invest in carbon-abating technologies and infrastructure to reach net-zero emissions by 2050. According to the UAE's H_2 roadmap, the nation is focusing on three key objectives:

1. Generate new sources of value through low-carbon H_2 and derivatives exports
2. Provide low-carbon H_2 and industrial derivative opportunities
3. Reach net-zero targets by 2050 in hard-to-abate sectors of the economy.[37]

A clear regulatory framework will enable these objectives, as will the development of new H_2 technologies through partnerships and research and development, allocated land for H_2 production facilities, access to financing and international capital markets, and government support to build H_2 infrastructure.[37]

To help reach its 2050 targets, the UAE plans to invest approximately $160 B in clean and renewable energy over the next 30 yr. The significant boost in renewable energy capacity will help fuel the production of green H_2/ammonia. According to Dipak Sakaria, an energy transition expert with the UAE's Ministry of Energy and Infrastructure, there were nearly 30 active H_2 projects under some form of development (e.g., proposed, planning, engineering, construction), with seven already passing through the financing stage.[38] The following are some of the more notable H_2 production projects under development in the UAE:

- Engie and Masdar formed a $5-B partnership to explore different routes to a green H_2 economy in the UAE. The JV aims to establish 2 GW of renewable energy capacity by 2030. For example, Engie and Masdar are working with Fertiglobe to build a 200-MW green ammonia production facility. Fertiglobe will be the sole offtaker, and plans to use it for carbon-neutral fertilizer production.
- Masdar is also working with Uniper to build a 1.3-GW solar plant to produce green H_2.
- Abu Dhabi National Oil Co. (ADNOC) is developing a 1-MMtpy blue ammonia plant at the TA'ZIZ Industrial Facility in Ruwais. The plant is scheduled to begin operations in 2025. ADNOC also plans to utilize a portion of natural gas from its multi-billion-dollar Hail and Shasha sour gas development to produce low-carbon H_2/ammonia. Although major onshore/offshore contracts were canceled in late April/early May, ADNOC is pursuing the mega project's development.
- Abu Dhabi plans to build a $1-B green ammonia production facility in the Khalifa Industrial Zone Abu Dhabi (KIZAD). The facility includes an 800-MW solar farm to produce green H_2, which will be converted into 200,000 tpy of green ammonia. The product is destined for the export market.
- Brooge is working with several companies to build a solar park and green ammonia production plant in Abu Dhabi. The projects will be built in two phases. Once fully operational, the export-oriented

Author

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facility will produce 1,950 tpd of green ammonia.

The UAE is also conducting feasibility studies on using low-carbon H_2 for mass transportation. This includes a network of H_2-fueling stations and a fleet of H_2-powered buses, among other H_2 infrastructure.

THE U.S.

In June, the U.S. Department of Energy (DOE) released the *U.S. National Clean Hydrogen Strategy and Roadmap*. This report builds on the Bipartisan Infrastructure Law (BIL) passed in November 2021, which allocated more than \$60 B for the U.S. DOE, including \$9.5 B to boost domestic green H_2 production. The report provides various pathways for U.S. producers to incrementally increase clean H_2 production to 10 MMtpy by 2030, 20 MMtpy by 2040 and up to 50 MMtpy by 2050. The roadmap[39]—part of the U.S.'s national decarbonization goals of 100% carbon pollution-free electricity by 2035 and net-zero greenhouse gas emissions by 2050—details three key strategies to effectively maximize the U.S.'s clean H_2 production potential:

1. **Target strategic, high-impact uses for clean H_2.** This aspect focuses on using green H_2 to decarbonize heavy-to-abate industrial sectors, such as chemicals and petrochemicals production, oil refining, steelmaking and heavy-duty transportation, as well as increasing clean H_2 exports.
2. **Reducing the production cost of clean H_2.** This initiative is part of the U.S. DOE's *Energy Earthshot's Hydrogen Shot* program to reduce the cost of green H_2 production to \$1/kg within one decade (i.e., the 1-1-1 plan). Significant investments must be made in green H_2 production, infrastructure, storage and distribution, and supply chains, among several other areas to reach this goal.
3. **The development of H_2 hubs.** These regional networks will enable producers and consumers to share infrastructure (e.g., distribution, production, storage) to facilitate green H_2 usage and build H_2 economies around major demand centers. The U.S. DOE has allocated \$8 B to establish six–10 regional clean H_2 hubs in the country. Of the nearly 80 concept papers received, the U.S. DOE invited more than 30 groups to submit a full application for potential funding. The U.S. DOE plans to begin announcing funding awards in Q4. According to the U.S. H_2 roadmap, midstream infrastructure investments must scale to \$2 B/yr–\$3 B/yr from 2023–2030, increasing to \$15 B/yr–\$20 B/yr from 2030–2050. These investments will not only grow regional H_2 networks to distribute green H_2 to demand centers but will also build a national H_2 network.

The overall national action plan for clean H_2 in the U.S. is shown in **FIG. 12.**

Active projects/initiatives. Numerous H_2 projects have been announced or have already commenced operations to meet these ambitious goals. **FIG. 13** shows a snapshot of operational H_2 production installations and announced projects in the U.S. These production plants and announced projects represent approximately 12 MMtpy of H_2 production capacity in the U.S.

At the time of this publication, the GEI database was tracking more than 170 active H_2 projects in the U.S. These projects represent a total CAPEX of more than \$200 B. When broken down by location, most active H_2 projects are in Texas (18%), California (16%) and Louisiana (7%)—nearly 20% of active H_2 projects are still in early planning/proposal stages, and exact locations have not been publicly announced (e.g., U.S. Gulf Coast). Most projects under development will take a green pathway (55%) to produce H_2, followed by a blue route (41%).

More than two dozen H_2 projects under development in the U.S. have a CAPEX of more than \$1 B. These projects range from green H_2 production to fuel power generation to help decarbonize domestic industrial sectors (e.g., refining, petrochemicals production) and establish a robust green ammonia value chain for domestic use and exports, and energy storage, among others. Several examples of these capital-intensive projects include the \$7.5-B Ascension Clean Energy project; the \$4.6-B St. Charles Clean Fuels project; Air Products' \$4.5-B Clean Energy Complex and \$4-B Wilbarger H_2 production facility; the Advanced Clean Energy Storage (ACES) project; ExxonMobil's 1-Bft^{3}d blue H_2 facility in Baytown, Texas; the \$4-B Lake Charles Methanol blue methanol complex; Nutrien's \$2-B, 1.2-MMtpy clean ammonia facility in

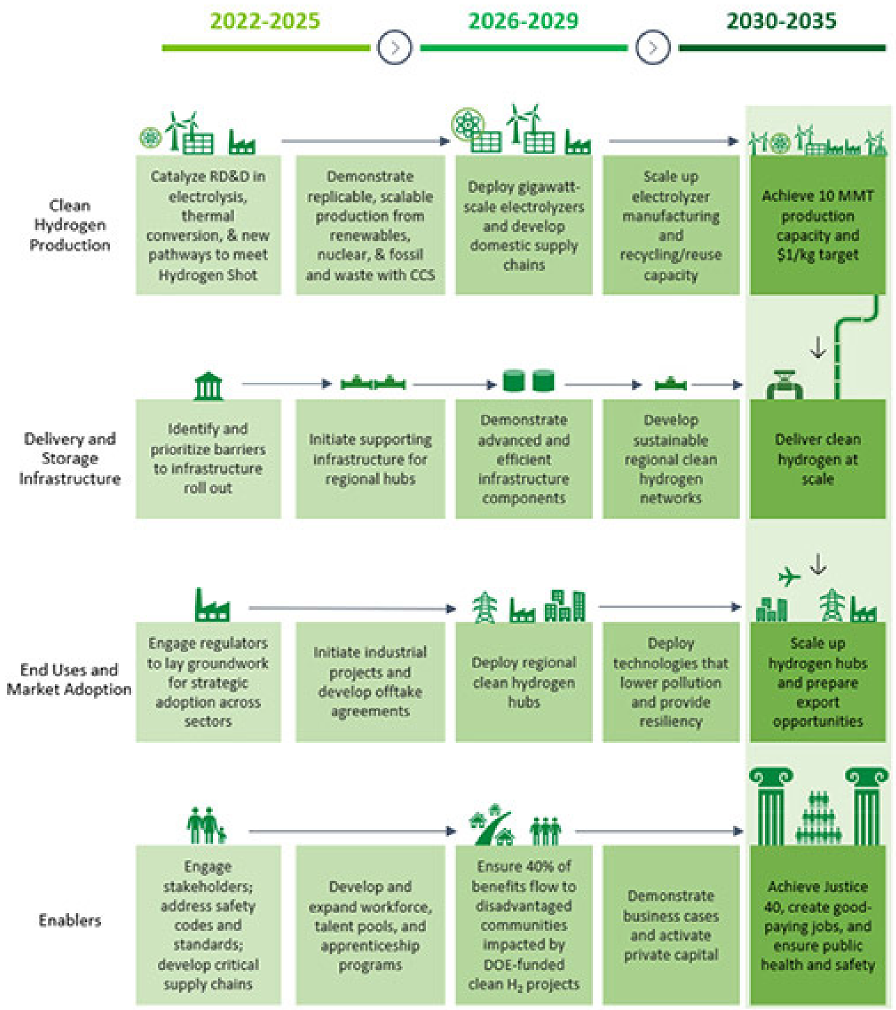

FIG. 12. The national action plan for clean H2 in the U.S.39 Source: U.S. DOE.

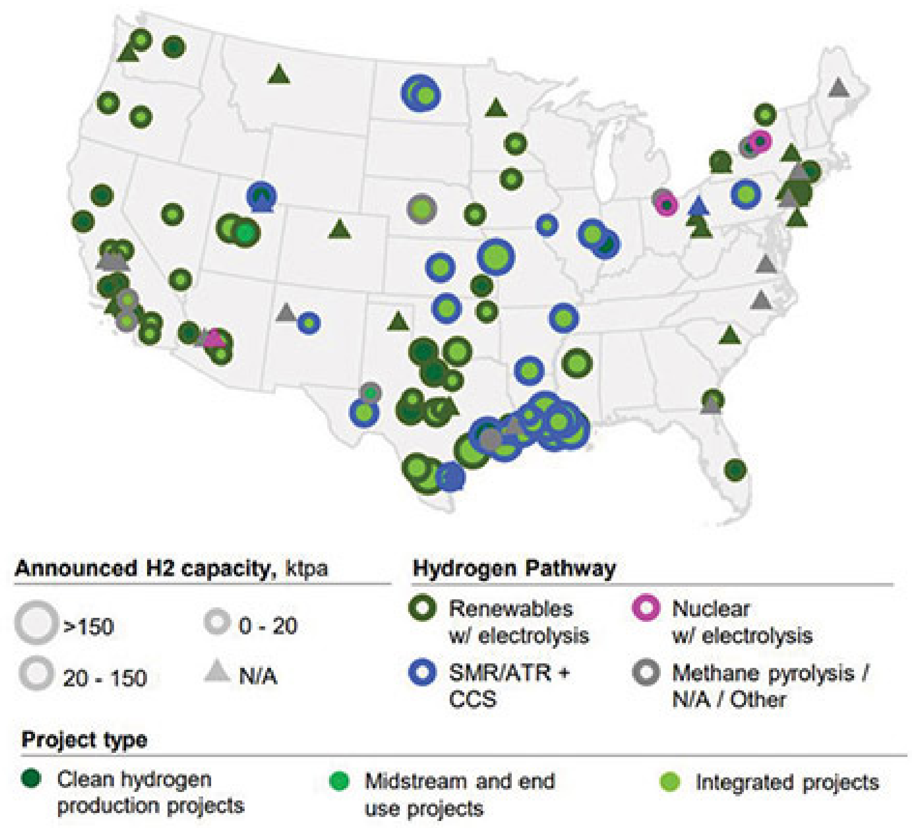

FIG. 13. Operational and active H2 production projects in the U.S. These installations/projects represent approximately 12 MMtpy of H2 production capacity.39 Source: U.S. DOE.

Geismar, Louisiana; CF Industries' multi-billion-dollar green ammonia facilities in Oklahoma and Louisiana; Yara and Enbridge's nearly \$3-B blue ammonia plant; and several others.

These capital-intensive projects—along with numerous infrastructure investments (e.g., H_2 fueling centers, H_2 pipelines)—are only a portion of the more than 170 active H_2 projects in the U.S. With the enactment of the BIL and subsequent funding from the U.S. DOE to support clean H_2 development, additional public and private investments will likely be made to significantly boost low-/zero-carbon H_2 production and distribution domestically.

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