The 2024 hydrogen report

Clean technology is on the march

By Maura D. Garvey, President of Intelligas Consulting LLC

In January 2023, the US captive on-purpose hydrogen production capacity stood at approximately 2.9 million cubic feet per day (mmcf/d). This describes hydrogen produced on-site for immediate use in an industrial context.

According to the US Department of Energy (DOE), 68% of this capacity was utilized in petroleum processing. The 2023 capacity figure was stable compared with the previous two years, while production declined in other parts of the world. About 21% of the hydrogen produced was used in fertilizer manufacturing.

Hydrogen production in the US predominantly derives from steam methane reforming, which isolates and collects the hydrogen contained in natural gas streams.

The US boasts 1,600 miles of hydrogen pipelines and significant hydrogen production facilities in nearly every state. As new innovations, applications, and blue and green sourcing channels continue to emerge, our understanding of hydrogen markets is constantly evolving. The major hydrogen-producing states are California, Louisiana, and Texas. Today, almost all the hydrogen produced in the US is primarily used in the industrial sector for oil refining, fertilizer manufacturing, and chemical production. Other uses for hydrogen include treating metals, producing fertilizer, and processing foods.

The US merchant liquid hydrogen market is poised for significant growth, driven by increasing demand across several key sectors, including aerospace, automotive, and industrial applications. The market is changing due to advancements in technology and increased investments aimed at enhancing hydrogen production and infrastructure. Liquid hydrogen is critical in aerospace for rocket fuel due to its high energy content and efficiency. It's also increasingly used in the automotive sector, particularly for fuel cell vehicles, which similarly benefit from hydrogen's high energy density.

From January 2023 to January 2024, the US saw notable advances and investments in hydrogen infrastructure and technology. Early in 2023, initiatives aimed at expanding hydrogen production were launched, notably leveraging existing infrastructure like nuclear power stations. A key example is New York's Nine Mile Point Nuclear Power Station, which started producing clean hydrogen in a pioneering effort in the nuclear sector. The move was part of a wider trend of integrating hydrogen production into diverse energy systems to boost clean energy efficiency and output.

Government support

Throughout 2023, the DOE launched major funding initiatives to foster research, development, and deployment of clean hydrogen technologies. Significant investments were made to lower the cost of clean hydrogen, targeting the DOE's Hydrogen Shot goal of achieving $1 per kilogram within ten years. This strong governmental support is instrumental in pushing forward a robust hydrogen economy in the US, with expected continued expansion in hydrogen capacity and utilization across various sectors.

The period reflects a dynamic phase of growth and innovation in the US hydrogen industry, propelled by government backing and industrial progress.

Let's review some recent history. The COVID-19 pandemic significantly impacted the refinery hydrogen business in 2020, as reduced population mobility decreased the demand for petroleum products. In 2022, Russia's invasion of Ukraine escalated energy demand to compensate for the loss of Russian supplies, leading to soaring Brent and WTI crude prices. In 2023, the average

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Brent crude price was $82 per barrel, compared with $101 per barrel in 2022 and $71 per barrel in 2021. The drop in oil prices in 2023 reflected a worsening global economic environment and COVID-19 flare-ups in China, which threatened demand growth and offset the impact of supply shortages due to sanctions on Russia, pushing up prices.

The forecast from the US Energy Information Administration (EIA) is that oil prices will fall in 2024. It expects that Brent crude oil prices will average $89/b in 2024, edging up to $87/b in 2025, with both figures down from $101/b in 2022. Three key factors play a part in this dynamic: Russia's oil production and ability to export petroleum products, several non-OPEC countries' ability to increase oil production, and China's demand outlook.

Despite fluctuating market conditions, hydrogen remains a robust growth area for the industrial gas sector. Large industrial gas companies consistently supply hydrogen to oil and gas refineries, chemical manufacturers, and food processors through on-site pipeline (OSP) services. Meanwhile, merchant liquid hydrogen, distributed in smaller volumes via tube trailers and cylinders, serves diverse applications such as metallurgy, electronics, aerospace, food hydrogenation, glass, power generation, and fuel cells – the latter showing the most rapid growth. Hydrogen fuel cells are increasingly viable as their costs decrease and performance improves. This report updates both the OSP and merchant hydrogen segments, highlighting the expansion of liquid hydrogen use in both stationary and mobile fuel cell technologies.

Distribution

Most hydrogen used in the US is produced at or close to where it is used – typically at large industrial sites. The infrastructure needed for distributing hydrogen to the nationwide network of fueling stations required for the widespread use of fuel cell electric vehicles still needs to be developed. The initial rollout for vehicles and stations focuses on building out these distribution networks, primarily in southern and northern California.

Currently, hydrogen is distributed through three methods – pipeline, high pressure (HP) tube trailers, and liquefied tankers. Pipeline is the least-expensive way to deliver large volumes of hydrogen, but the capacity is limited to the 1,600 miles of pipelines for hydrogen delivery are currently available in the US. These pipelines are located near large petroleum refineries and chemical plants in Illinois, California, and the Gulf Coast.

HP tube trailers are used to transport compressed hydrogen gas by truck, railcar, ship, or barge. This kind of trailer transport is expensive and used primarily for distances of 200 miles or less. Cryogenic liquefaction is a process that cools hydrogen to a temperature where it becomes a liquid. Although the liquefaction process is expensive, it enables hydrogen to be transported in liquefied tankers more efficiently (compared with HP tube trailers) over longer distances by truck, railcar, ship, or barge.

On-site supply

Most hydrogen today is supplied via pipeline to large users. The pipelines are located near large petroleum refineries and chemical plants in the Gulf Coast, California, and Illinois. In the US, OSP represents 85% of hydrogen supply. Steam methane reforming (SMR) of natural gas is the technology of choice for on-site hydrogen production and is currently the least expensive way to produce hydrogen. This process is used by most large users like refineries, fossil fuel processors, and ammonia producers, and it is used by the major gas companies to meet demand for OSP hydrogen. Steam reforming of natural gas is an efficient, economical, and widely used process for hydrogen production, and provides near- and mid-term energy security and environmental benefits.

The oil-refining industry leads hydrogen production in the US, especially in the Gulf Coast, where half the US refineries operate. The major hydrogen-producing states are Texas, Louisiana, and California. About 90% of hydrogen is sold to oil refining through sale of gas deals by industrial gas companies.

Hydrogen demand has increased substantially over the years because environmental regulations require the removal of sulfur from motor vehicle fuels and the processing/hydrocracking of heavier crudes. At the same time, the evolution of the shale gas industry, especially in the past decade, has slowed the demand for oil and therefore the need for hydrogen to process heavier crudes.

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Air Products, Linde plc, and Air Liquide are all major producers of on-site pipeline and merchant hydrogen in the North American market and together operate over 100 plants. Air Liquide, Air Products, and Linde all operate hydrogen pipelines in Texas, Louisiana, California, and Indiana to supply hydrogen to customers. All consider hydrogen a worldwide strategic growth platform. Matheson, through its recent acquisition of Linde's divested HyCO (Hydrogen and carbon monoxide) business, becomes the new fourth player in the US hydrogen on-site/pipeline business.

Natural gas is the main methane source for hydrogen production by industrial facilities and petroleum refineries. Landfill gas/biogas is also a source of hydrogen for several fuel cell power plants in the US. Biofuels and petroleum fuels are also potential methane sources.

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The colors of hydrogen

SMR splits natural gas into hydrogen and carbon dioxide (CO_2). But the CO_2 byproduct makes this a carbon-intensive process and is why hydrogen produced this way is called "gray" hydrogen as it is the least environmentally friendly of the three types.

Air Products announced in 2021 it will build, own, and operate a first-of-its-kind megaproject, which will produce over 750 mmcf/d of "blue" hydrogen in Ascension Parish, Louisiana. Blue products are produced utilizing hydrocarbons as a feedstock, with the CO_2 in the production process captured for permanent sequestration. At $4.5bn, it represents Air Products' largest-ever investment in the US. The megaproject is expected to be operational in 2026.

In February 2023, Linde announced it will build, own and operate an on-site complex which will include autothermal reforming with carbon capture, plus a large air separation plant. The new complex will be integrated into Linde's extensive Gulf Coast industrial gas infrastructure. It will supply clean hydrogen and nitrogen to OCI's 1.1 million tons-per-annum blue ammonia plant, which is the first greenfield blue ammonia facility of this scale to come onstream in the US. Linde will supply OCI with clean hydrogen by sequestering more than 1.7 million metric tons of carbon dioxide emissions each year.

In addition to supplying OCI, Linde will also use its extensive pipeline network to provide clean hydrogen to existing and new customers in the US Gulf Coast, addressing the increasing demand from companies to decarbonize their operations. The facility will also

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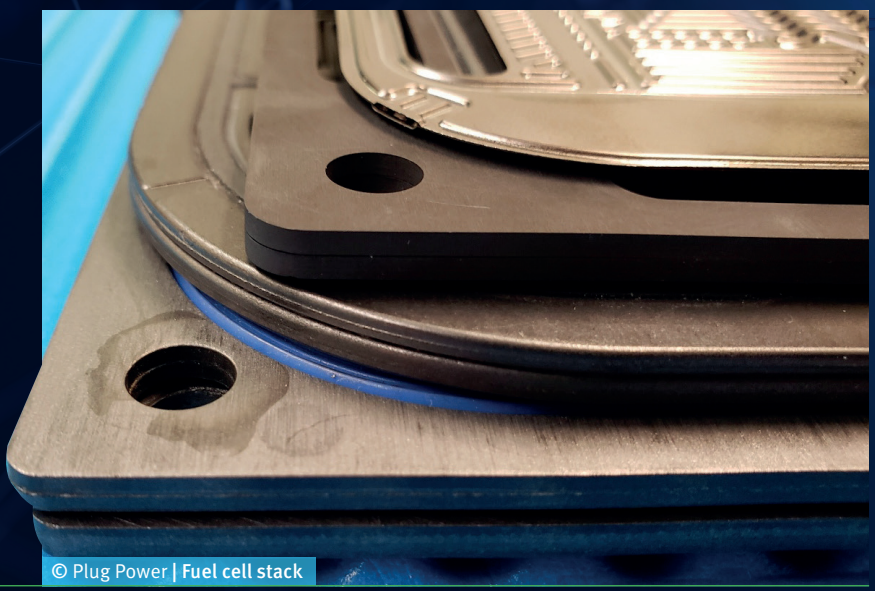
supply atmospheric and rare gases to existing and new customers. Linde's total investment will be approximately $1.8bn and the project is expected to start up in 2025.

Blue hydrogen is hydrogen, remember, that is produced through the process of SMR, where natural gas is the primary feedstock. The key aspect of blue hydrogen production is the capture and storage of the carbon dioxide (CO_2) emissions that result from the SMR process.

As its name suggests, the cleanest type of hydrogen is "green" hydrogen. It is produced by splitting water (H_2O) into hydrogen and oxygen via a process of electrolysis powered by renewable energy. This means that no CO_2 is created during production.

The Inflation Reduction Act of 2022 (IRA) includes clean energy tax credits and other provisions that should increase domestic renewable energy production. The IRA's clean energy incentives include many provisions for clean hydrogen and fuel cell technologies, either extending many existing federal tax credits, increasing existing federal tax credits, or creating new federal tax credits.



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Refinery hydrogen

Hydrogen plays a vital role in a whole host of refining operations, from hydrocracking, which is the reduction of heavy gas and gas oils to lower molecular weight components, to the treatment of gas streams and to catalytic reforming. In the latter, the gas is also used to prevent carbon from reacting with the catalyst to maintain the production of lighter hydrocarbons and extend the life of the catalyst.

According to data reported by *Oil and Gas Journal*, between January 2022 and January 2023, worldwide crude oil refining capacity increased from 93.2 million barrels per calendar day (MMb/cd) to 93.9 MMb/cd, for an increase in the average annual growth rate (AGR) of 0.8%, slowing from growth the year prior of 2.2%. A growth of 1.9% was experienced for the US while the rest of the world increased by 0.6% per year. The average annual growth over the past five years worldwide increased by 0.4% while the US growth for the same period declined by 1% per year. The US comprises 17.7% of global crude oil refining capacity.

According to the International Renewable Energy Agency (IRENA), global hydrogen production is around 75 million tons per year as pure hydrogen, and an additional 45 million tons per year as part of a mix of gases. Most hydrogen today is made from fossil fuels, with two-thirds being pure hydrogen and one-third mixed with other gases. Hydrogen is used in refineries, as a feedstock in the chemical industry, in heat and power generation, and as part of a mix of gases in steel production.

Hydrogen plants are located next to or near (piped) oil refineries to produce hydrogen for use in the production of cleaner burning fuels. According to the US Energy Information Administration, by January 2023, US captive on purpose hydrogen production capacity was 2.9 million cubic feet per day (mmcf/d), flat since 2021, but down by 1% from five years ago. In March 2023, ExxonMobil announced the beginning of operations at the expansion of its Beaumont refinery, adding 250,000 b/d of capacity. The Beaumont expansion is the first major refinery capacity expansion to come online since the Covid-19 pandemic, which prompted several refinery capacity closures over the course of 2020 and 2021.

Merchant hydrogen

Merchant hydrogen is defined as hydrogen that is generated on site or in a central production facility and sold to a consumer by pipeline, bulk tank, or cylinder truck delivery. The merchant hydrogen business supplies a broad range of markets with small to medium hydrogen requirements via bulk liquid, tube trailer, and cylinders. These markets include electronics, float glass, hydrogenation of fat and oils for food, chemical and petrochemical, cosmetics, pharmaceuticals, metals and heat treating, alternative energy (fueling stations and fuel cells), and research markets. The chemicals

industry uses hydrogen to make ammonia, fertilizer, and methanol. Metal processors and heat treaters use hydrogen to help create bright and shiny stainless steel, improving product quality while reducing waste. The electronics market uses hydrogen in manufacturing integrated circuits. The power industry uses hydrogen fuel cell batteries for backup power for remote telecommunications or mission-critical applications. Fuel cells can be used in a wide range of applications, including transportation, material handling, stationary, portable, and emergency backup power applications.

Stationary and backup power and material-handling equipment are some of the potentially largest and fastest growing markets for liquid hydrogen. Transportation and energy storage are emerging sectors for hydrogen and fuel cells. Recent improvements in fuel cell cost and performance are giving the technology economic viability. The increased number of retail hydrogen fueling locations in select markets is supporting the initial rollout of hydrogen-fueled cars.

According to the Department of Energy, as of 2023 there were 59 open retail hydrogen stations in the US. Additionally, there are at least 50 stations in various stages of planning or construction. Most of the existing and planned stations are in California, with one in Hawaii and five planned for the northeastern states. The northeastern stations are part of a 12-station network planned by Air Liquide and Toyota Motor Sales USA, Inc. The stations will be in Hartford, Connecticut; Braintree, Massachusetts; Mansfield, Massachusetts; and Bronx, New York, and will span approximately 300 miles across five states. The stations will provide the infrastructure needed for hydrogen fuel cell electric vehicles (FCEVs). There are also private stations supporting fleets and some primarily used for demonstration and research.

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Merchant liquid hydrogen capacity was flat for several years until 2016, when Airgas opened the Calvert City, KY plant with a capacity of 11 tons per day (tpd), bringing total merchant capacity to about 283 tpd. Four more new merchant liquid hydrogen plant builds were then announced, which started up between 2021 and 2022, increasing cryogenic liquid capacity by 92 tpd to over 430 tpd.

Air Products continued this trend when it announced in March 2022 plans to build a 10 tpd green liquid hydrogen production facility in Casa Grande, Arizona. The zero-carbon liquid hydrogen facility started up in 2023 and its product targets the hydrogen mobility market in California and other locations requiring zero-carbon hydrogen.

Linde (merged with Praxair in 2018) is the largest supplier of liquid hydrogen in the US and has expanded its hydrogen production and supply network in the region over the past decade. Linde has plans to increase its green hydrogen production capacity in the US by building a new 35-megawatt PEM electrolyzer in Niagara Falls, NY, where it has an existing byproduct liquid hydrogen plant. This facility is set to more than double Linde's green liquid hydrogen production capacity in the US and is expected to commence operations by 2025.

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Green hydrogen from Plug Power

Plug Power is a leading provider of turnkey hydrogen solutions for the global green hydrogen economy. It has put six green hydrogen liquid facilities on the drawing board since 2019 in the US. This is all part of its plans for its North American green hydrogen production network. The company's national network of plants

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is in Tennessee, New York, Pennsylvania, Georgia, California, and Louisiana. The network will supply 500 metric tpd of liquid green hydrogen by 2025, replacing 4.3 million metric tons of CO_2 emissions, and 1,000 tpd globally by 2028.

In April 2024, Plug Power achieved full operational capacity at its hydrogen production facilities in Georgia and Tennessee, significantly enhancing its supply chain efficiencies. The Georgia facility, notable for housing the largest Proton Exchange Membrane (PEM) electrolyzer in the US, is producing 15 tons per day of liquid hydrogen. Similarly, the Tennessee plant has reached its full production capacity of 10 tons per day.

This increase in production capacity enables Plug Power to meet about half of its current customer demand for green hydrogen. The company's network now includes 40 cryogenic trailers that distribute liquid hydrogen across the US for various applications, including material handling operations, fuel cell electric vehicle fleets, and stationary power applications.

Further expansion is anticipated with the Louisiana plant, a joint venture with Olin Corporation, which is expected to contribute an additional 15 tons per day by the end of Q3 2024. This expansion will boost Plug Power's internal production capacity to 40 tons per day, covering most of its customer needs.

Plug Power is also developing a green hydrogen highway across North America and Europe and has constructed a state-of-the-art Gigafactory for producing electrolyzers and fuel cells. The company plans to have several green hydrogen production plants operational by the end of 2028, aiming to deliver its green hydrogen solutions directly to customers and through joint venture partnerships across a range of sectors.

In January 2023, Plug Power was awarded an order to deliver two 30 tpd hydrogen liquefaction systems to TC Energy Corp. These 30 tpd hydrogen liquefaction systems utilize a hydrogen refrigeration cycle and bring to market one of the most energy-efficient designs to date. The two hydrogen liquefiers are scheduled for delivery in Q2 or Q3 2024 and will serve TC Energy facilities in North America. Specific locations for these facilities have not been finalized as they are still in the process of finalizing sites for hydrogen production and distribution hubs.

This increase in capacity is being built because capacity utilization has continued to increase from high growth in the stationary and portable fuel cell market and in liquid hydrogen fueling stations.

Introducing FuelCell Energy

Entering this market is FuelCell Energy (FCE), which has developed platforms to helium businesses with power generation, carbon capture, hydrogen production, and energy storage.

FCE as recently launched its first commercial hydrogen production facility. The Tri-generation system in the Port of Long Beach utilizes directed bio-gas to make electricity, transportation grade hydrogen, and water. FCE has several methods to make hydrogen and decarbonize it through its carbonate and solid oxide fuel cells. The solid oxide electrolyzer efficiently converts power and water into hydrogen, while the carbonate fuel cells can be configured to capture flue gas carbon while producing power, water, CO_2, and hydrogen.

The fuel cells are modular so they can be grouped in sufficient numbers to scale up and make merchant product but currently FCE is focused on on-site generation.

Future outlook

As you can tell, significant strides and sustained growth in the US hydrogen sector have been made throughout the past five years.

This underscores the stability of hydrogen production capacity, which largely supports industries like petroleum processing and fertilizer manufacturing. The period was also marked by robust government initiatives aimed at enhancing hydrogen production capabilities, including leveraging existing infrastructure. This remains a strong growth platform for the industrial gas industry.

The efforts of the DOE to reduce the costs of clean hydrogen through substantial investments and governmental support, along with industrial advancements, have positioned hydrogen as a key player in the transition to cleaner energy sources. This positions hydrogen in a dynamic growth phase despite the backdrop of fluctuating global oil prices and economic uncertainties affected by geopolitical tensions. The continued expansion of hydrogen's applications, from industrial uses to emerging technologies in fuel cells, underscores the evolving landscape of energy production, where hydrogen plays a pivotal role in shaping a sustainable energy future. gw

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