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H_2Go! Hydrogen's path to cleaner energy

ROCKEFELLER INSIGHTS

Portfolio Opportunities

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H_2...Go!

Hydrogen is both the lightest and most abundant element in the universe. It has a long history as a fuel source going back to the 18th century. Today's focus on decarbonizing the planet has spurred a renewed interest in hydrogen—can it play a pivotal role in developing a greener source of energy?

Many factors seem to be falling into place that should encourage greater usage of hydrogen: global government policy support; greater availability of low-cost renewable energy sources such as wind and solar; technology enhancements that lower production costs; and innovation that expands the market potential across a wide array of end markets. Investors are likely to be reading and hearing a lot more about specific hydrogen-related opportunities in the years to come.

The importance of hydrogen

Along with electrification, hydrogen is expected to become an important building block in achieving decarbonization goals throughout the world. The greatest Greenhouse Gas (GHG) emissions occur within agriculture, industrial and energy production, the heating of buildings, and transportation—many of which can be mitigated with hydrogen use.

It is estimated that around 20% of global carbon emissions could be abated by hydrogen today, with the hydrogen economy eventually reaching $2.5 trillion.[1] Hydrogen is becoming more readily accepted as a low-carbon fuel for sectors that either cannot use electrification or in which it is difficult to abate emissions, such as long-distance transportation, steel and cement processing and heating.

1. Bernstein Research, June 2021

What makes hydrogen an attractive fuel option?

Hydrogen is the most common element on earth but exists in molecular forms such as water or hydrocarbons. While water is, for the most part, in abundant supply, a chemical process (electrolysis) is required to separate hydrogen and oxygen from water. If the energy used to power the electrolysis comes from renewable sources, the result is green hydrogen (more on this later) and there will be no GHG emissions. However, if other energy sources are employed, some carbon emissions can occur.

Once hydrogen is separated from water, it can be stored in either a liquid or gaseous state, but it does require significant storage capacity. The advantages of hydrogen, however, are that it can flow through pipelines 2x-3x faster than natural gas and can use existing natural gas pipeline infrastructure, making transportation relatively efficient.[2]

Hydrogen has a high energy density, or the amount of stored energy per unit volume. One kilogram of hydrogen contains 195x more energy than a one-kilogram lithium-ion battery pack and as much as one gallon of diesel fuel.[3]

A higher energy density allows for greater driving ranges and heavier towing, making hydrogen particularly well suited for heavy-duty transportation, power, and long duration energy storage markets. Hydrogen is, however, less efficient in some instances than batteries, suggesting that it makes sense to use battery technology for some applications and hydrogen for others.

Hydrogen production: the world of electrolyzers and fuel cells

To date, most hydrogen has been produced using fossil fuels, but that is rapidly changing with policy evolution and cost reductions. The most common process is steam methane reforming (SMR), whereby natural gas or coal is reacted with high temperature steam, creating hydrogen and carbon by-products.

This process results in grey hydrogen. If, however, the carbon is captured and stored (usually underground), then that results in a more environmentally-friendly outcome creating blue hydrogen.

Directionally, the industry is moving toward the process of splitting water into its constituent molecules hydrogen and oxygen, in which oxygen is released into the air while the hydrogen can be stored as either a liquid or a gas. This is water electrolysis and the hardware required is called an electrolyzer.

If the electricity used to power the electrolysis comes from renewable sources, there are no

2. CreditSights, 10/15/2020
3. Bernstein Research, 8/26/2022

GHG emissions associated with the process; this is green hydrogen production. Once hydrogen is produced, it can be stored for future use or it can be converted into other sources of energy, like ammonia or methane, that are more easily transported.

Alternatively, the hydrogen produced can also be re-converted back to electricity using a fuel cell—think of this as a "reverse electrolyzer" that consumes oxygen and hydrogen and combines them together, releasing electricity and water.

This conversion is an efficient process with minimal heat loss vs. a gasoline engine in which over 50% of heat is lost. Fuel cells therefore have become increasingly used in transportation. This technology offers zero-emission driving via an on-board fuel cell that converts hydrogen to electricity; it was also the technology that powered the Apollo mission to space.[4]

Fuel cell electric vehicles (FCEVs) tackle long distances and heavy loads

The growth of the fuel cell electric vehicles (FCEVs) market and the importance of hydrogen in the process suggest that we spend some time on this topic. A fuel cell, like a battery electric vehicle (BEV), uses an electric motor to propel the car.

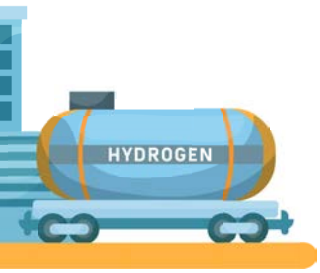
The difference is that BEVs draw electricity from the battery while the fuel cell constantly generates electricity through electrolysis, which drives the motor. Hydrogen fuel cells offer flexibility, because of hydrogen's high energy density, longer distances may be driven, and heavier loads towed, before refueling is necessary. These features suggest that hydrogen FCEVs may be more appropriately used by fleet operators and in heavy-duty trucks.

So far, FCEVs are more popular in Asia than in North America or Europe, where auto manufacturers have focused on BEVs. However, we note an increasing number of partnerships amongst the major auto firms to develop fuel cell technology.

4. Bank of America, 9/23/2020

THE MANY COLORS OF HYDROGEN

While this report is focused mainly on green hydrogen and its environmental benefits, there are several "colors" of hydrogen worth noting. The differences depend on the inputs and processes used to produce hydrogen.



PINK YELLOW GREEN BLUE GREY BROWN

COLOR	SOURCE	PROCESS	EMISSIONS
Pink	Nuclear	Electrolysis	No CO_2
Yellow	Energy grid	Electrolysis	Emissions vary
Green	Wind, solar, water	Electrolysis	No CO_2
Blue*	Natural gas	Steam methane reforming	Carbon monoxide
Grey	Natural gas	Steam methane reforming	CO_2
Brown	Coal, oil	Gasification	CO_2

Source: CNBC, 6/4/2022
* Blue hydrogen is considered carbon neutral if CO is converted to CO2 and carbon is captured and stored

It's not all glass half-full

Hydrogen offers significant advantages as a potential clean energy source. Water is readily available in many locations, it is clean burning, it can be transported via existing pipelines, and it can be a resource for renewable energy storage (i.e., it is not always sunny or windy).

However, hydrogen production has its associated challenges. For one, the production process is somewhat inefficient, as hydrogen is produced and then converted back into an energy source—much of the energy is lost in the conversion process.

While battery technology returns around 90% of energy input, production and storage of hydrogen results in around 63% energy loss.[5]

Water should not be a constraint in most cases, but a supply of minerals such as nickel, platinum or iridium are required for certain types of electrolysis.

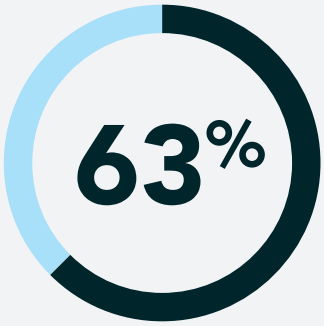
And the cost and availability of electrolyzers is certainly an issue. Green hydrogen can only be more quickly produced if electrolyzer capacity grows.

Since hydrogen gas needs to be compressed for storage, space can be a limitation. Storage solutions, such as pressurized containers for short time periods, or salt or rock caverns, depleted oil & gas fields, or aquifers for longer time periods, will be needed.

Hydrogen can be transformed into ammonia or methanol, but there are costs associated with this conversion.

Distribution then becomes dependent on volume and distance; for short distances, trucks or pipelines can be used, but additional pipelines will likely be needed. For longer distances, onshore or subsea pipelines are necessary.

FCEVs require refueling and currently there is not enough infrastructure for mass adoption. For heavy duty trucks, hydrogen tanks, like diesel, can be filled quickly, while batteries are heavier and limit driving ranges. However, batteries are less costly, and the battery charging infrastructure is expanding.



energy lost in production and storage of hydrogen

5. CNBC, 1/6 2022

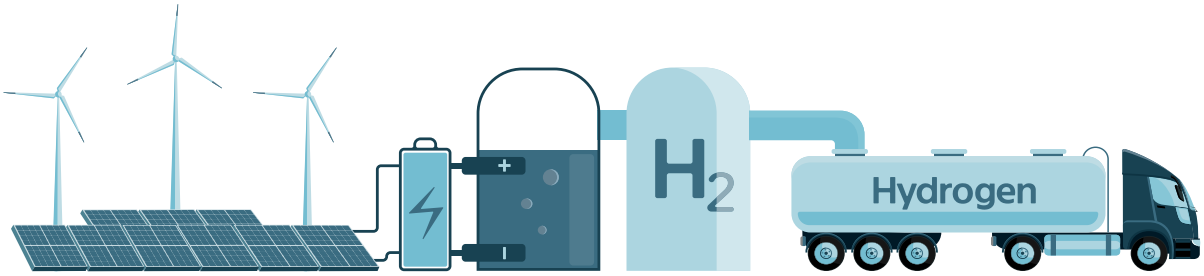
Technology and cost enhancements keep us optimistic

In just the past couple of years, there have been technological and process enhancements resulting in lower costs of hydrogen production. Blue and green hydrogen have the lowest carbon intensity but are costly compared to grey hydrogen production.

It is expected that green hydrogen costs will fall substantially by 2030 as technology scales and renewables become more plentiful. Most hydrogen produced today is grey, which can cost between $1-$2/kg to produce, while green hydrogen costs are closer to $5/kg.[6]

It is anticipated that green hydrogen costs will be below $2/kg by 2030 and could be at parity with grey hydrogen by 2025 and at parity with diesel fuel by 2027.[7]

Electrolyzer manufacturers are developing designs aimed at bringing down the cost of producing green hydrogen, including improving the efficiency of the process. Even so, mass adoption is unlikely without policy support.



Coordinated global policy support for the hydrogen industry

Fortunately for the hydrogen industry, in 2022 the U.S., Europe and China all announced policy support for low carbon hydrogen in the form of either subsidies (tax credits) and/or targeted levels of hydrogen use.

In the U.S. this support came through the Inflation Reduction Act; in Europe through the Re-Power EU Plan; and in China through the Hydrogen Development Plan.[8] As a result, there has been a significant acceleration in the number and scale of announced hydrogen projects.

Over 50 countries have committed to hydrogen roadmaps – with 1000 announced projects, of which 90% are for green hydrogen production.[9]

China has one of the world's most supportive hydrogen policies, as the country aims to have one million FCEVs on the road by 2030.[10] Other countries active in hydrogen development are Japan, Australia, Canada, Korea, Chile and parts of the Middle East.

6. Wall Street Journal, 11/11/2022
7. Goldman Sachs, 2/4/2022
8. Bernstein Research, 1/9/2023
9. Bernstein Research, September 2022
10. Bernstein Research, September 2022

U.S. support for hydrogen has intensified with passage of recent legislation

The U.S.'s hydrogen policy has evolved significantly in the past couple of years. The Bipartisan Infrastructure Law (Nov 2021) allocated $9.5 billion for development of hydrogen as a clean energy source.

Additionally, the U.S. Department of Energy (DOE) has published a "Hydrogen Program Plan" and "Hydrogen Strategy" documents. These provide a strategic framework for deployment and growth of U.S.'s hydrogen economy, specifying a research & development plan, establishing regional hydrogen hubs, and identifying a national energy strategy for hydrogen. The DOE envisions 6-10 hubs across the U.S., with each receiving funding of between $600 million and $1 billion.[11]

Hydrogen received another boost from the recent Inflation Reduction Act, or IRA (Aug 2022), that provides for a 10-year clean hydrogen production tax credit (PTC). The PTC will apply to clean hydrogen produced domestically after December 31, 2022, and to facilities constructed prior to January 1, 2033. The amount of the PTC is dependent on the resulting GHG emissions. Standard credits are for $0.60/kg of clean hydrogen produced, with the ability to obtain $3.00/kg if certain labor requirements are met.

With the PTC, green hydrogen production can be more cost effective than either natural gas-produced grey hydrogen or fossil fuels. This suggests that green ammonia or green methanol projects could be profitable within just a few years. The PTC incentives are likely to accelerate the development of infrastructure to support hydrogen use and spur innovation to find new markets for hydrogen. U.S. government figures estimate that there will be $13 billion in green hydrogen PTCs claimed over the next decade.[12]

Prior to the IRA passage, the hydrogen market in the U.S. had been evolving for years. The fuel cell manufacturers have been improving the technology for several decades. However, legislation has renewed a focus on accelerating hydrogen-related projects.

In 2022, 120 hydrogen start-ups privately raised $2.6 billion, nearly a 50% increase over 2021 levels.[13] And electrolyzer shipments rose 160% in 2022 vs. 2021; they are expected to grow another 200% in 2023.[14] California has been one of the more progressive U.S. states in supporting hydrogen development.

The state offers incentives to build out hydrogen refueling infrastructure; the city of Lancaster, CA is partnering with companies to build what would be the world's largest renewable hydrogen plant – that could supply CA's fueling stations.

As affordability, scalability and policy support converge, there is likely to be significant capital allocated to the hydrogen economy. Investment bank Goldman Sachs expects the total addressable market for hydrogen to double from 2022 to 2030 – to around $250 billion.[15] But the firm also notes the add-on effect of increased demand for power, water and electrolyzers – and the possibility that hydrogen becomes a cross-border tradeable asset for those countries that can produce amounts that exceed domestic demand.

11. Wolfe Research, 9/11/2022
12. Bernstein Research, 1/9/2023
13. Wall Street Journal, Pitchbook, 1/14/2023
14. Bernstein Research, 1/9/2023
15. Goldman Sachs, 2/4/2022

CLEAN PATHWAYS

PRACTICAL USES OF GREEN HYDROGEN

Cleaning up heavy industry

The most obvious applications of green hydrogen are found among existing hydrogen end markets that are not yet "green." The largest consumers of hydrogen today are oil refining (removes sulphur content in crude, hydrocracking) and chemicals processing industries.

Most hydrogen today is used as a feedstock for ammonia, fertilizer and methanol production. And almost all of the approximately 10 million tons of hydrogen used is processed from natural gas via steam methane reforming, releasing carbon by-products.

If green hydrogen were used instead, CO2 emissions would decline significantly. Hydrogen is perhaps the best low carbon option to reduce emissions from high temperature heat processes such as the production of steel (hydrogen could replace coal-fired or oxygen blast furnaces), cement, iron, aluminum and glass.

Hydrogen could also be a solution for industrial processes that are hard to decarbonize or where electrification is not an option, such as plastics.

Planes, trains and...trucks?

While heavy industry is the most obvious application of hydrogen, the benefits of hydrogen use in transportation are arguably the most exciting.

While BEVs make sense for the passenger car market, at least for now, they are not likely suitable for the segments of transportation that create substantial GHG emissions and are more difficult to decarbonize – such as heavy duty trucking, aviation and rail transport.

Hydrogen has an advantage in the long haul and heavy truck market because of challenges in powering heavy vehicles with batteries; fuel cells have lower weight and offer faster refueling times. In a heavy-duty Class 8 truck, it can take three hours to charge the battery vs. 10 minutes to fill a 50kg tank on a hydrogen FCEV, and does not drain power from the grid.

FCEVs can carry 20%-25% more cargo based on the lower weight of the fuel cell vs. additional powertrain weight if a battery were on board.[16] But FCEVs are expensive, between the cost of the fuel cell and hydrogen storage. For long range trucks, it is expected that FCEVs will be cost competitive with BEVs around 2028.[17]

The challenge is building a hydrogen refueling infrastructure. At the end of 2022, there were about 1000 hydrogen refueling stations globally.[18] While both BEV and FCEV technologies are likely to co-exist, stricter emissions requirements have spurred a faster uptake of FCEVs and a series of partnerships among auto/truck manufacturers to develop fuel cell technology.

Forklifts is one market where fuel cells are already cost competitive with battery vehicles. Globally there are about six million forklifts with average lifetimes of around four years.[19]

Electric/hydrogen forklifts offer environmental benefits, improved performance and lower maintenance costs vs. diesel-powered forklifts. They also have higher productivity rates because of faster and more efficient refueling. Fuel cell vendor Plug Power anticipates that hydrogen-powered forklifts can save a typical 200-lift distribution center around $900,000 annually.[20]

16. Bernstein Research, 8/26/2022
17. Bernstein Research, June 2021
18. Bernstein Research, 1/9/2023
19. Bernstein Research, June 2021
20. Bernstein Research, June 2021

CLEAN PATHWAYS

PRACTICAL USES OF GREEN HYDROGEN

Aviation solutions are in their infancy

Aviation is one of the toughest transport sectors to decarbonize, although significant changes are underway, as standard jet fuel (kerosene) is a carbon emitter. The most realistic option is to use biofuels or to produce synthetic kerosene from hydrogen, but these are costly options. Alternatively, hydrogen fuel cells could be used for short flights or hydrogen in the form of synthetic fuels for longer flights, where most carbon emissions occur.

The addressable market for hydrogen-powered aviation is small, with experimentation in commuter or regional planes. ZeroAvia is a start-up that completed the first test flights of a hydrogen fuel cell-powered aircraft in September of 2020.[21] The plane was powered by high pressure hydrogen stored in tanks in the wings and a fuel cell.

In August of 2022, ZeroAvia announced an investment by American Airlines to potentially order up to 100 of its hydrogen electric engines for use in regional planes, and the company has pre-orders from United Airlines, Alaska Air and British Airways.

ZeroAvia's propulsion system has fuel cells that turn hydrogen into electricity that turn the propellers, whereas pure hydrogen planes will burn hydrogen in a conventional engine. Beyond regional flights, however, the weight of fuel cells will be a challenge. Interestingly though, aircraft manufacturer Airbus has unveiled three hydrogen-powered projects, with two covering long distance routes. Airbus plans to use liquid hydrogen to power its first zero-emission aircraft – likely in service around 2035.[22]

Hydrogen-powered trains are here

Today, most locomotives are diesel-powered; electrification or replacement with fuel cells would go a long way toward reducing emissions and noise levels. Trains powered by hydrogen can be retrofitted to existing diesel trains, or can switch between electrification and hydrogen where tracks are not electrified.

Although the up-front costs of hydrogen trains are higher, the longer term economic and environmental profile is attractive. Railways with longer routes, especially in rural areas, and/or those with demanding schedules, are more likely to choose hydrogen as a fuel source.

The first hydrogen-powered passenger train was developed by French multinational Alstom and entered operation in 2018. It can run for 18 hours without refueling and can be refueled in 20 minutes.[23] By May of 2021, Alstom's hydrogen trains had carried passengers over 110,000 miles in Europe, with cost parity to diesel or electrified trains.[24] Since then, other European, Asian and Canadian rails have tested the technology and partnered to build fuel cell trains.

The fuel cell market for transportation is expected to reach $360 billion over the next few years, with the largest market share gains in on-road applications, amongst trucks, buses and other fleet vehicles.[25] Although penetration rates in aviation will likely be lower, we expect fuel cells to become more popular within rail and marine transport.

21. Wall Street Journal, 8/17/2022
22. Bernstein Research, June 2021
23. Goldman Sachs, 8/11/2020
24. Wall Street Journal, 5/26/2021
25. Bernstein Research, 5/11/2022

Hydrogen a valuable resource for the power grid

Hydrogen could be useful in providing energy for the power grid and as a source of energy storage. The challenge with renewable energy is intermittency (i.e., it is not always sunny or windy) and seasonality. Hydrogen-fired gas turbines can offer flexibility for the intermittency issue.

Hydrogen can balance power from the grid and, since it can be stored, is already used as a source of back-up power for hospitals and data/cloud computing centers.

Along with wind, solar and nuclear, hydrogen is a good choice to decarbonize the power sector – as it has similar efficiency as natural gas power plants with near-zero emissions. Hydrogen can be a long-duration energy storage solution for the power grid as it can be stored in fuel cells and existing natural gas turbines and re-connected back to the grid. This can offset the seasonal mismatch between power demand and renewable output.

Excess renewable energy, like solar on a sunny day, could be stored as hydrogen and then released as energy at a point in the future. Utilities could potentially store energy in the summer for use in the winter.

Many utilities are engaged in large-scale hydrogen projects. NextEra Energy, the U.S.'s largest producer of renewable energy, has been successfully using excess solar energy to produce hydrogen. On-site hydrogen storage then provides power to local grids during peak demand. Next Era also has two proprietary technologies expected to come on-line in 2026 and 2027 to develop green hydrogen with renewables.[26]

Virginia-based AES Corporation, another utility that operates renewable energy power plants, is teaming up with industrial gas firm Air Products to build a "mega-scale" wind and solar-powered green hydrogen plant in North Texas, scheduled to begin operations in 2027.[27]

Long Ridge, on the Ohio River, is the first purpose-built plant in the U.S. to generate power with hydrogen fuel. It uses various blends of hydrogen and natural gas, using General Electric Power's turbines and has the capacity to power 400,000 homes.[28]

A few years ago, Los Angeles Department of Water & Power, the nation's largest municipal utility, converted a formerly coal-fired power plant in Utah to run on natural gas and hydrogen, produced with excess wind and solar power.[29]

While these examples are forward progress in the realm of clean energy production and storage, it also means an increased demand for renewables—benefitting those entities with ample supplies.

26. Wolfe Research, 1/29/2023
27. Seeking Alpha, 12/8/2022
28. GE.com, 4/21/2022
29. Wall Street Journal, 9/5/2020
30. CNBC, 1/6/2022

WHO PARTICIPATES IN THE HYDROGEN SUPPLY CHAIN?

Several types of companies have been identified in this report that play a role in the production, delivery, storage and application of green hydrogen. We identify the major participants as follows:

INTEGRATED HYDROGEN INFRASTRUCTURE

These companies are typically providers of industrial gas that produce, distribute and transport hydrogen through pipelines and liquid hydrogen tankers.

ELECTROLYZER AND FUEL CELL MANUFACTURERS

These firms typically have decades of experience developing improved technology to lower the cost of these products; they often partner with vehicle manufacturers and oil companies to leverage the technology.

ENERGY PRODUCERS

The European firms are generally ahead of the U.S. oil companies in producing hydrogen and biofuels for refining and other operations; these companies partner with industrials on FCEVs and refueling stations.

INDUSTRIALS

General industrials that supply equipment and/or systems are integral in developing new applications of green hydrogen.

UTILITIES

Many utilities are developing renewable power sources and partnering to build and manage plants that produce hydrogen.

NOTE:

The table on the next page identifies several participants in the current hydrogen supply chain. Please note that this is a sampling and not a complete list.

Any references to a company or publicly traded entity are strictly for illustrative purposes only and are not intended to be construed as investment advice or as a recommendation to purchase, sell or hold any security.

Selective Hydrogen Supply Chain Participants

Stock	Symbol	Brief Description
Hydrogen Infrastructure		
Air Products	APD	Unique exposure to green hydrogen across multiple projects. Partner in developing NEOM, the world's largest green hydrogen plant, in Saudi Arabia.
Linde Plc	LIN	Industrial gas company that will use hydroelectric power from Niagara Falls to make green hydrogen; pursuing major hydrogen clean energy projects
Fuel Cell Companies		
Plug Power	PLUG	Manufactures fuel cell systems primarily for the materials handling market. Building a green hydrogen facility in Georgia for liquid hydrogen production for forklifts.
Bloom Energy Corp	BE	Manufactures power generation systems that utilize fuel cell technology to generate hydrogen and electricity.
Energy Producers		
Chevron	CVX	Exploring the feasibility to utilize hydrogen in rail transport. Investing in hydrogen refueling stations primarily in California. Partnering with Cummins to develop commercially viable hydrogen opportunities for industry, FCEVs and use of hydrogen in Chevron's refineries.
Shell Plc	SHEL	Owns Europe's largest green hydrogen plant in Germany. Presence in China with renewable power electrolyzer and hydrogen fueling stations, with plans to develop in the U.S.
TotalEnergies	TTE	Developing France's largest renewable hydrogen site, powered by solar farms with the green hydrogen produced used to make biofuels. Mass producing clean and low carbon hydrogen as fuel sources.
Industrials		
Cummins Inc	CMI	Major global manufacturer of electrolyzers. Partnering with Alstom to develop hydrogen powered locomotives. Partnering with Chevron to leverage CMI's electrolyzer technology for FCEVs and refineries.
Chart Industries	GTLS	Provides transportation and storage solutions for liquid hydrogen, as well as hydrogen tanks for refueling.
Caterpillar Inc	CAT	Partnering with Burlington Northern Santa Fe and Chevron to confirm the feasibility of hydrogen fuel for long-haul rail.
Emerson Electric	EMR	Develops software and systems that integrate off-shore wind and natural gas to produce hydrogen at sea.
Utilities		
NextEra Energy	NEE	Its NextEra Energy Resources (NEER) is one of the world's largest renewable energy generators. NEER's wind and solar farms produce green hydrogen. It's most recent hydrogen project uses solar power with on-site hydrogen storage that will provide power to local grids during peak demand.
AES Corp	AES	Renewable energy producer. Partnering with Air Products to develop a green hydrogen facility using a combination of wind and solar power. The North Texas facility will be the U.S.' largest.
Exchange Traded Funds		
Global X Hydrogen ETF	HYDR	The fund closely tracks the parameters of the Solactive Global Hydrogen Index.
Defiance Next Gen H2	HDRO	The fund closely tracks the parameters of the BlueStar Global Hydrogen and NextGen Fuel Cell Index.

Closing thoughts

As a source of cleaner energy, hydrogen has many advantages, as evidenced by the rapid pace of development in just the last few years.

It certainly has associated challenges, as well, but recent legislation enhances the cost competitiveness, and has pulled forward the estimated market potential of green hydrogen.

Investment opportunities will likely span across a variety of industries and countries and should become more widespread over the next few years.

We leave readers with a quote from John Kerry, special presidential envoy for climate issues, at the Department of Energy's 2021 Hydrogen Summit,

"In my travels around the world I can't name a country that hasn't expressed excitement about hydrogen. From Saudi Arabia to India to Germany to Japan we're setting up hydrogen partnerships around the world to advance this critical technology that every country understands has the opportunity to play a vital role in the clean energy transition."[30]