# The Greening of Hydrogen

## Can it be a Major Contributor to the Energy Transition?

By Martin Flusberg
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### Hydrogen's Role in Energy

Hydrogen, which consists of 1 one proton and 1 electron, is the simplest and most abundant element on earth. When hydrogen burns, it generates energy in the form of heat, with water as a by-product. That means energy created from hydrogen generates no atmosphere-warming carbon dioxide, making it one of many potential energy sources that could help reduce carbon emissions and slow global warming.

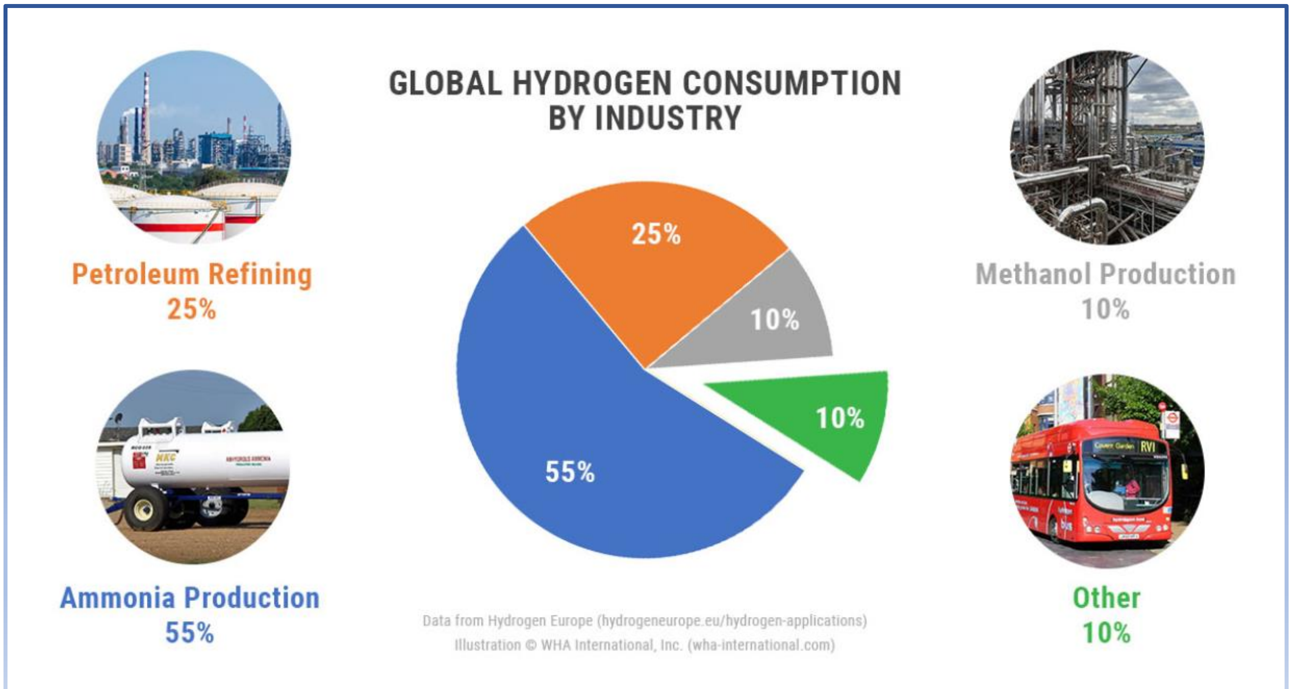
In addition, one of the pros of hydrogen energy is that it is very versatile. It can generate electricity, heat buildings, power vehicles and even produce industrial chemicals.

Hydrogen is not an energy source but can serve as an energy carrier which stores and can deliver usable energy. However, hydrogen doesn't exist by itself and therefore must be produced from compounds that contain it. Currently, most hydrogen is produced from fossil fuels, in particular natural gas. Electricity—from the grid or from renewable sources such as biomass, geothermal, solar, or wind—is also currently used to produce hydrogen. Hydrogen can also be produced through steam methane *reforming* - a high-temperature process in which steam reacts with a hydrocarbon fuel to produce hydrogen.

Another hydrogen production method takes water and separates it into oxygen and hydrogen through a process called *electrolysis*. Biological processes can also produce hydrogen through biological reactions using microbes such as bacteria and microalgae. In these processes, microbes consume plant material and produce hydrogen gas.

Finally, there are also several ways to produce hydrogen using sunlight, including photobiological, photoelectrochemical, photovoltaic-driven electrolysis, and solar thermochemical processes.

Despite hydrogen's versatility (staffers at the US Department of Energy have referred to it as the *"Swiss Army knife of energy"*) 80% of hydrogen today is used for just 2 purposes: petroleum refining and ammonia production for use in fertilizers.




Source: WHA International

That being said, an indication of hydrogen's versatility is the multiple uses that constitute the Other category in the chart above (other than transportation which will be addressed later), including:

- **Food:** Hydrogen has been used to turn unsaturated fats into saturated oils and fats, including hydrogenated vegetable oils like margarine and butter spreads.
- **Metalworking:** Hydrogen is used in multiple applications including metal alloying and iron flash-making.
- **Welding:** Atomic hydrogen welding (AHW) is a type of arc welding which utilizes a hydrogen environment.
- **Flat Glass Production:** A mixture of hydrogen and nitrogen is used to prevent oxidation and therefore defects during manufacturing.
- **Electronics Manufacturing**: Hydrogen is used to create semiconductors, LEDs, displays, photovoltaic segments, and other electronics.

- **Medical:** Hydrogen is used to create hydrogen peroxide ($H_2O_2$). Recently, hydrogen gas has also been studied as a possible therapeutic gas for several diseases.

Demand for hydrogen, which has grown more than threefold since 1975, continues to rise. In the US alone 10 million metric tons (MMT) were generated in 2022. Worldwide the demand for hydrogen reached an estimated 87 million metric tons in 2022, and, according to the International Energy Agency (IEA) could grow to 500 to 600 MMT by 2050.

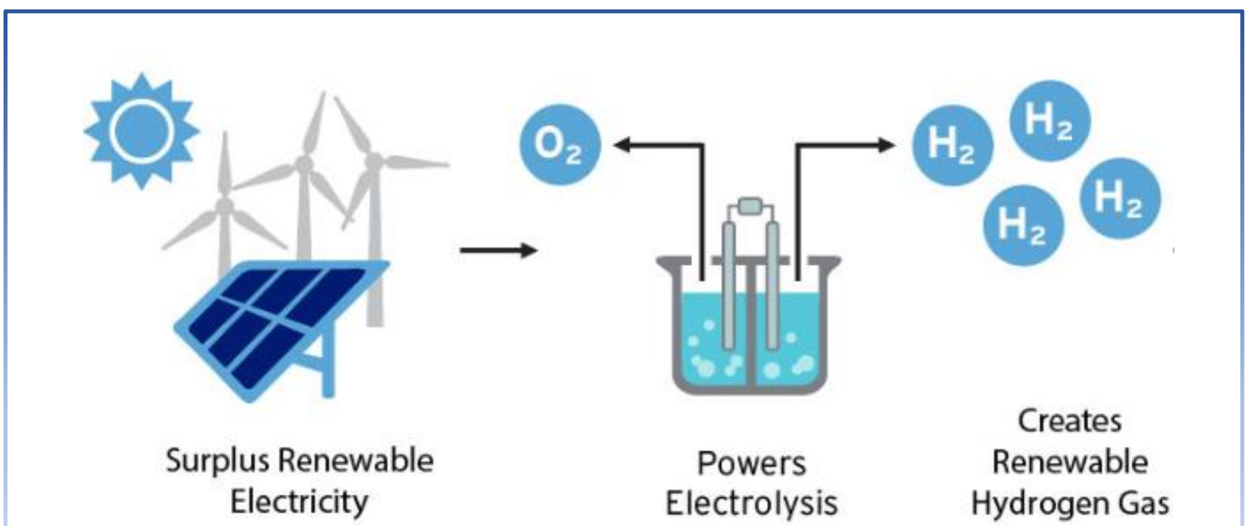
## Green Hydrogen

While hydrogen delivers clean energy, creating hydrogen and transforming it into a useful format requires energy — and that energy is generally not renewable. As noted earlier, natural gas is currently the primary source of hydrogen, accounting for around 75% of annual global hydrogen production. This accounts for about 6% of global natural gas use. Gas is followed by coal, due to its dominant role in China, and hydrogen generation accounts for about 2% of coal use.

As a consequence, production of hydrogen is responsible for $CO_2$ emissions of around 830 million tons per year, equivalent to the $CO_2$ emissions of the United Kingdom and Indonesia combined, and representing 2% of total global emissions

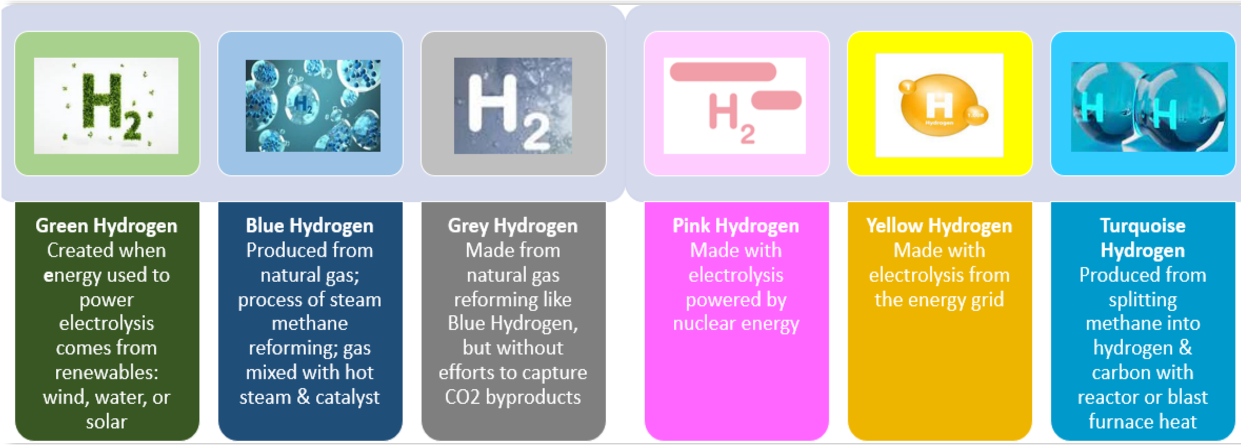
But as also noted earlier, it is possible to create hydrogen without the use of fossil fuels.

**Green Hydrogen** is hydrogen that is created by the electrolysis of water powered entirely by renewable energy. That totally eliminates $CO_2$ and makes for a totally clean fuel source.




Source: Fuel Cell & Hydrogen Association

In general, all other hydrogen is referred to as Grey Energy. But some in the industry apply different colors to different ways of generating hydrogen. Here's the list:




**The Color of Hydrogen**

So, it sounds like Green Hydrogen has the potential to be a major player in the energy transition.

## Not so Fast?

But there are still some major challenges to overcome before the use of Green Hydrogen can be widely expanded.

For more than 20 years, proponents of hydrogen have been promising a future of clean energy. But while the pace of new Green Hydrogen projects is accelerating, most are still at an early stage of development. There were only 33 green hydrogen facilities operational across North America as of 2022. The current green hydrogen capacity in the region is only 690 thousand metric tons per year.

But the pace is picking up. Here are 5 Green Hydrogen projects under development in the US that are expected to be operational at some point in 2023.

### 1. St. Gabriel Green Hydrogen Plant

The project in Louisiana will have a capacity of 15 tons per day and is intended to supply the fuel cell market. To accomplish this, Plug Power and Olin Corporation launched a joint venture called Hidrogenii. Olin will produce hydrogen and provide operational support, while Plug Power will be responsible for marketing the hydrogen and providing logistical support.

**2. Kingsland Green Hydrogen Plant**

This project, in Camden County, Georgia, is also operated by Plug Power and intended to produce 15 tons of hydrogen per day, which will be liquefied and stored before being loaded for transport.

Plug Power has a national network of hydrogen plants in different regions, including New York, Tennessee, Texas, and California. By 2025, Plug Power expects to produce 500 tons/day of liquid green hydrogen; by 2028, the company predicts 1,000 tons/day.


Image (not photograph) of Plug Power Green Hydrogen Facility

**3. Sauk Valley Green Hydrogen Plant**

This is the first green hydrogen project operated by Invenergy in Illinois. The project will generate green hydrogen by utilizing power from Invenergy's co-located solar plant and Ohmium International's low carbon PEM electrolyzer technology, which produces 6kg of hydrogen per hour.

The plant will have a capacity of 52 tons per year and will be able to store 400kg of hydrogen on site.

**4. Casa Grande Green Hydrogen Plant**

This green hydrogen plant in Casa Grande, Arizona is owned and will be operated by Air Products. The facility is expected to produce 10 metric tons per day and its product will be sold to the hydrogen for mobility market in California and other locations.

The entire facility will be powered by renewable power and use two ThyssenKrupp Nucera electrolyzers to produce gaseous hydrogen, which will be converted to liquid hydrogen using Air Products' proprietary technology. The site will also include a terminal for distributing hydrogen to customer locations.

**5. Donaldsonville Green Hydrogen Project**

This project, which will be managed by CF Industries, will be the largest of its kind in North America. It is a 20MW alkaline water electrolysis plant to produce green hydrogen at the company's Donaldsonville, Louisiana manufacturing complex. The plant will be integrated into existing ammonia synthesis loops and produce 20,000 tons of green ammonia per year.

CF Industries will allocate renewable energy purchased across its network from available grid-connected sources to match 100% of the electricity the electrolyzer needs to separate water into carbon-free hydrogen and oxygen. The project also involves a partnership with ThyssenKrupp.

But before the use of Green Hydrogen can become widespread there is a major problem that needs to be addressed. Currently, the process of electrolysis is relatively energy intensive and expensive. According to the International Energy Agency (IEA), the cost of producing Green Hydrogen ranges from $3.20 to $7.70 per kilogram. This is in contrast to a cost of $.50 to $1.70 per kilogram to produce hydrogen using natural gas.

Additionally, hydrogen is a gas at room temperature and must be stored in high-pressure or cryogenic tanks, which is also quite expensive.

The good news is that the U.S. Department of Energy's (DOE) is working towards reducing the cost of producing Green Hydrogen. Their **Energy Earthshots** Initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade.

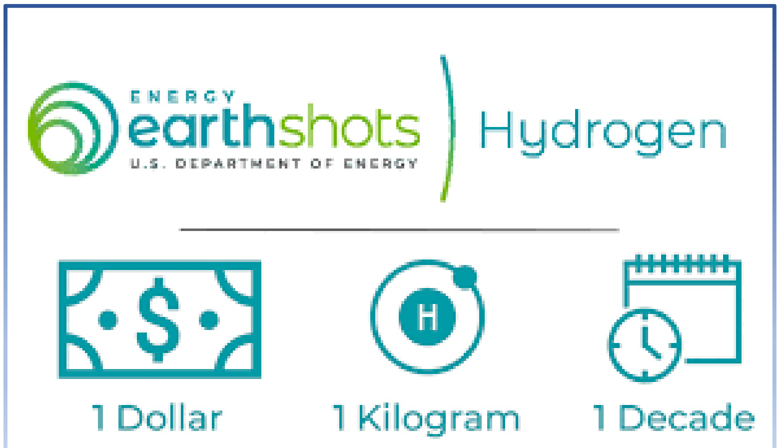
The first Energy Earthshot – **Hydrogen Shot** - launched in June 2021 and seeks to reduce the cost of clean hydrogen by 80% to around $1 per kilogram by 2030.

The Hydrogen Shot establishes a framework and foundation for clean hydrogen deployment. It includes support for demonstration projects and will sponsor a series of events to engage stakeholders, including Hydrogen Shot Summits, the first of which took place in August 2021.

There are three pathways DOE has cited for reducing the cost of Green Hydrogen:

- Improving the efficiency, durability, and manufacturing volume of electrolyzers.
- Improving pyrolysis, which generates solid carbon rather than carbon dioxide as a byproduct.
- Various experimental technologies. One example is referred to as the *photoelectrochemical approach (PEC),* where sunlight and specialized semiconductors are used to break water into sunlight and hydrogen.

Achieving the Hydrogen Shot's 80% cost reduction goal can unlock new markets for hydrogen, including steel manufacturing, clean ammonia, energy storage, and heavy-duty trucks. If the Hydrogen Shot goals are achieved, scenarios show the opportunity for at least a 5-fold increase in Green Hydrogen use by 2030.




As part of the U.S. Infrastructure Investment and Jobs Act, DOE established clean hydrogen initiatives to accelerate domestic production, deployment, and use of Green Hydrogen. $9.5 billion was allocated to fund at least 4 Regional Clean Hydrogen Hubs, with the aim of creating jobs and expanding the use of clean hydrogen in the industrial sector ($8B allocation): a Clean Hydrogen Electrolysis Program intended to reduce the cost of hydrogen produced from clean electricity ($1B allocation); and Clean Hydrogen Manufacturing and Recycling Programs to support the domestic clean hydrogen supply chains ($500M allocation).

Other countries across the world are also investing in Green Hydrogen in an aim to bring down costs – while simultaneously increasing production.

So, hopefully, we will begin to see our way towards much less expensive Green Hydrogen over the coming decade, which should help ensure that it becomes a key part of the energy transition.

Where else might we see expanded use of Green Hydrogen as costs begin to drop?

## Potential Uses for Green Hydrogen

### Transportation

Hydrogen is an energy carrier and fuel that, when fed into a fuel cell, can be used to power road vehicles, including cars, buses, and trucks. There has been a lot of discussion over the past 20 years about the role hydrogen can play in reducing emissions in the transportation sector. For example, it has been noted that hydrogen fuel cell–powered vehicles travel longer distances using less energy than gasoline powered vehicles; a hydrogen fuel-cell vehicle with 1 kg of hydrogen can drive approximately

60 miles, compared to conventional vehicles, which get about 25 miles on a gallon of gasoline. Several auto companies introduced hydrogen-fueled cars.

But with the recent significant increase in all electric vehicles over the past couple of years the interest in using hydrogen to power automobiles has declined markedly. Backers of hydrogen fuel cell vs. battery-powered cars point to the long time it takes to charge a battery compared to the time it takes to add hydrogen. EV proponents point to battery swapping as an approach that will eliminate this disparity, although there has been very limited progress with battery swapping. On the other hand, EV chargers have been getting faster, and there are still a large number of EV owners that charge at home or at work where the time to charge is not that much of an issue. Promotors of battery power also point out that for every joule you put in a battery you get 90% of it back, whereas in producing and storing hydrogen you get only about 35% of the energy back out.

One of the major barriers to using hydrogen to fuel cars is the lack of infrastructure. While hydrogen vehicles and power plants exist, there were only 54 hydrogen fueling stations in the United States at the end of 2022. (Even the leading country in this space, China, only had about 250 hydrogen fueling stations). By contrast, at that time there were about 168,000 gas stations in the US with about 1.5 million pumps, and more than 50,000 public charging stations for EVs with over 150,000 chargers.


Source: Pixabay

As interest in hydrogen-fueled cars has waned, one by one auto manufacturers are abandoning plans for hydrogen-fueled cars. For example, Honda ceased production of its Clarity hydrogen fuel cell vehicle in August 2021. So, it appears that automobiles are not likely to be a major user of hydrogen – even Green Hydrogen.

However, hydrogen and fuel cells are still being promoted as a means for reducing emissions in heavy-duty vehicles, including trucks and buses, which make up 5% of vehicles on US roads, are responsible for more than 20% of transportation emissions, and are the largest contributor to mobile nitrogen-oxide emissions. Larger vehicles require larger EV batteries, which increases their weight, which in turn increases their energy use. Hydrogen can potentially reduce energy usage, increase range, and address the frequent need to fuel rapidly for some fleets. That being said, there remains a lot of activity around electric, battery-powered long-haul trucks, and more work is being done on battery swapping for heavy duty trucks than for cars. So the jury is still out whether and when a major market for hydrogen fueled trucks takes off.

There has also been considerable discussion about using hydrogen for maritime fuel.

Green Hydrogen could play a key role in the maritime industry's journey towards decarbonization. Many in the shipping industry recognize hydrogen's potential, but the barriers to implementing H2 technology are substantial.

That being said, the **H2Ports**, project funded largely by the European Union (EU) is intended to demonstrate and validate two innovative solutions based on fuel cell technologies and a hydrogen mobile supply station specifically designed for the project. This is being conducted at the Port of Valencia, Spain. A Reach Stacker to be tested in MSC Terminal Valencia and a Yard Tractor to be tested in Valencia Terminal Europa have been selected as appropriate for the use of fuel cells in port facilities. (In April 2023, the Port of Valencia also became the first port in the world to use a 4×4 truck tractor unit powered by Green Hydrogen to move containers within its terminals). The project will run for two years to analyze ways of improving the energy efficiency, performance, and safety of operations with fuel cell port equipment. The pilots will be the first experiences of the use of hydrogen technologies in port handling equipment in Europe, with the Port Authority of Valencia (APV) having a goal to convert its docks into a 'zero emissions' zone by 2030.


Image Courtesy of H2Ports

DNV, a German-based organization, which bills itself as the world's leading classification society and is a recognized advisor to the maritime industry, is focused on enhancing safety, quality, energy efficiency and environmental performance of the global shipping industry. It recently led a consortium of 26 organizations that issued a Handbook for Hydrogen-fueled Vessels, which creates a roadmap towards safe hydrogen operations using fuel cells.

The Handbook suggests that more testing is needed on the safety aspects of handling, storing and bunkering of hydrogen. A key takeaway is that testing needs to focus on the impact of leakage (a known hydrogen risk) including the potential detonation risk if there is a leak. The Handbook points out a range of other safety related issues as well. The Handbook also goes on to report that moving hydrogen as a fuel from land-based applications to maritime use will be no small feat. With the International Maritime Organization's regulatory framework, class rules and different interpretations from countries and ports to consider, navigating the regulatory landscape will be challenging. (The Handbook offers a comprehensive overview of the regulatory environment).

Another factor to consider is that the ports themselves will play a significant role in determining whether hydrogen is a usable fuel by controlling what fuels are available for the ships in the port to use - and when.

As an example of an alternative to hydrogen, the Maritime and Port Authority of Singapore believes that by 2025 it will be ready to offer ammonia bunkering, around the same time that the first ammonia fueled ships are expected to be delivered. (The Port Authority stepped back from earlier expectations that ammonia fueling trials would happen by the end of 2023 – largely due to safety concerns).

And speaking of ammonia; as noted earlier more than half of hydrogen across the world is used to produce ammonia, the vast majority of which is used to make fertilizer. But, because so little of the hydrogen generated is Green Hydrogen, there are several companies around the world experimenting with technologies to create ammonia without hydrogen. For example, a company based in Israel (transparency alert; I am a shareholder in the company) is generating ammonia from nitrogen and water only; bypassing the use of hydrogen that is the basis of the well-known Haber-Bosch process. The Haber-Bosch process converts atmospheric nitrogen to ammonia by a reaction using a metal catalyst under high temperatures and pressures. This process is credited with massively increasing food production and helping to feed the world's rapidly growing population over the past 100 years**.** If the approaches to bypass Haber-Bosch prove effective – and the example above is only 1 of multiple companies tacking this issue - the clean ammonia that is created will free up huge amounts of Green Hydrogen to be used for other purposes

Hydrogen has also been proposed as an efficient fuel for aviation. The International Air Transport Association (IATA), among other organizations, has been discussing liquid hydrogen as a potential low-carbon fuel for aviation.

Hydrogen-powered aircraft will require fuel cell or adapted turbine-based powertrains, cryogenic tanks, and hydrogen infrastructure at airports.

**Airbus** is working to develop hydrogen-powered aircraft and is adapting its A380 MSN001 test aircraft to be its demonstrator for its ZEROe program. The aircraft will still use conventional engines for propulsion but provide a flight environment to test hydrogen systems. Airbus aspires to create a 200-seat, 2,300-mile range hydrogen combustion airliner, but will start with a 100-seat, 1,150-mile range aircraft which they expect to be available by 2035.


Startups **H2FLY** and **ZeroAvia** are developing smaller aircraft powered by hydrogen fuel cells in a much shorter timeframe. In 2020, ZeroAvia successfully flew a six seat Piper Malibu with a 250kW hydrogen-electric propulsion system and is poised to test a 600kW-equipped, 19-seater Dornier 228 (image on the right).

ZeroAvia aims to certify its 600kW powertrain so it can be used in 9 to 19 seat aircraft by 2025 – the same timescale within which H2FLY expects to start operations with its 300kW five-seater aircraft.

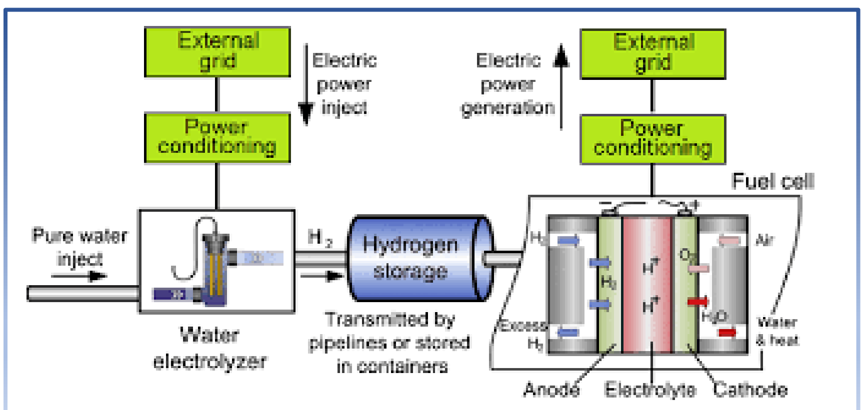
H2FLY's aircraft will use technologies proven on the company's HY4 hydrogen retrofitted Pipistrel Taurus G4 glider, first developed at the German Aerospace Centre.

In parallel, both H2FLY and ZeroAvia are working on upscaled 2MW powertrains as well.

**Storing Renewable Energy**

Hydrogen provides a viable way to store renewable energy for an extended period. Despite the fact that the overall efficiency of hydrogen today is lower than that of other storage technologies, interest in hydrogen energy storage is growing due to the much higher storage capacity compared to pumped hydro (the most common form of storage) or batteries (which are a fast-growing storage option but have limited capacities).

The "round-trip efficiency" of converting electricity to hydrogen, then burning that hydrogen to generate electricity, is only about 35 percent. In other words, for every megawatt-hour of output 3.5 MWh are consumed. But that becomes much less of an issue if the objective is long-duration storage measured in weeks or even months vs. short-term storage measured in hours.




Hydrogen Storage System Topology – Courtesy of ResearchGate

**Advanced Clean Energy Storage Delta** is building an energy storage facility in Utah which is designed to store hydrogen for months. The facility will convert excess solar and wind power generated into hydrogen during the spring and fall and save it to generate electricity to cover shortfalls in renewable power supply during summer heat waves and droughts and cloudy and/or windless winter months. The developer received a loan of $500 million from the US Department of Energy for the project.

The other major hydrogen storage project in the US is being undertaken by Pacific Gas & Electric in coordination with energy storage company **Energy Vault** in Calistoga, California. The project integrates a short duration battery system with long duration fuel cells plus hydrogen storage for situations as described earlier.

The hydrogen storage option appears to be further along outside the US in countries such as Germany, Denmark, and Australia. But there is definite interest in the US, and the availability of Green Hydrogen should accelerate the use of hydrogen grid storage.

## Bottom Line

Green Hydrogen clearly has a role to play in achieving the transition to a clean energy environment. There are major initiatives across the world aimed at greening hydrogen, including US DOE's Hydrogen Shot. Billions of dollars are being spent to help create Green Hydrogen.

Hydrogen's versatility means it can be used in a lot of different ways. That implies that if some roles proposed for hydrogen – such as for powering cars – do not pan out, there are multiple other options for its use.

But the process of rolling out Green Hydrogen on a major scale will not be a rapid one. There are safety concerns regarding hydrogen in some markets. Green Hydrogen is still a relatively expensive alternative. It will take a while to get the costs down to a point where Green Hydrogen can be widely adopted.

But we appear to be on the way.