The Economics of Green Hydrogen

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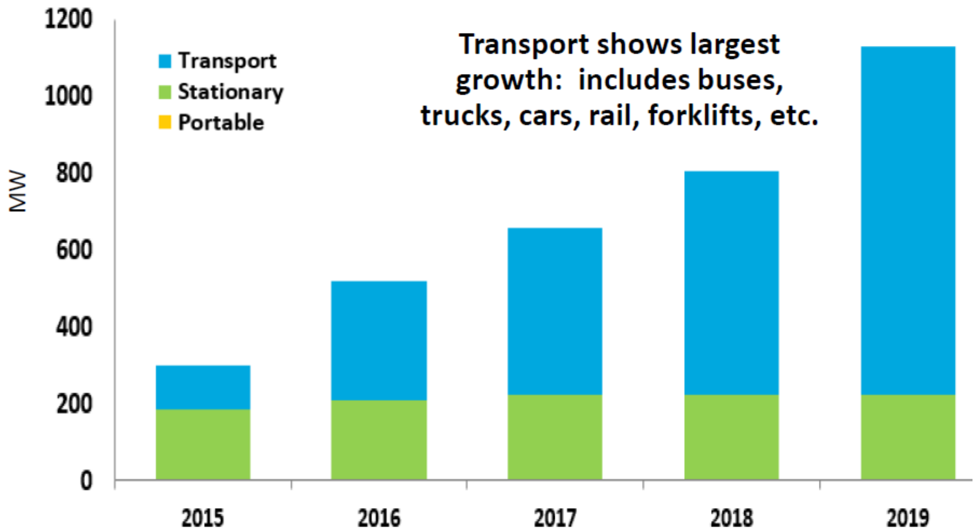
1. Introduction

Most that have looked at the economics of the title fuel believe that it will play an important role in the transition to a greenhouse gas (GHG) free economy in future years. However the big question is, when?

First of all this answer depends not only on the specific application of this fuel, and the technology to convert the fuel back to electric energy, but also the application profile and where it is being evaluated. For instance, in a recent post (linked below) on clean backup generation, I found a similar hydrogen-fuel-cell application in large, long-range buses (commonly called coaches). I also found an economic evaluation where fuel-cell-electric long-range buses would be competitive with battery-electric long range buses as soon as the mid-2020s (see section 4.1 in the post linked below).

https://energycentral.com/c/pip/clean-backup-generation

Both hydrogen fuel-cell electric buses and hydrogen fuel cells used for other transport applications are rapidly increasing shipments globally. See the graphic below from a 2021 U.S. Department of Energy presentation.[1]



In this post we will look at the general case – how much is it likely to cost to produce and store green hydrogen at various points in the future. We will also look at other factors that will reduce or increase these costs. We will review two generation methods using hydrogen. Finally we will end with a brief section that contains links to various other publications that will let readers drill down for additional information regarding specific applications.

[1] Dr. Sunita Satyapal, U.S. Department of Energy Hydrogen and Fuel Cell Technologies, Office Overview, Jan, 2021, https://www.energy.gov/sites/default/files/2021-03/hfto-satyapal-overview-jan-2021.pdf

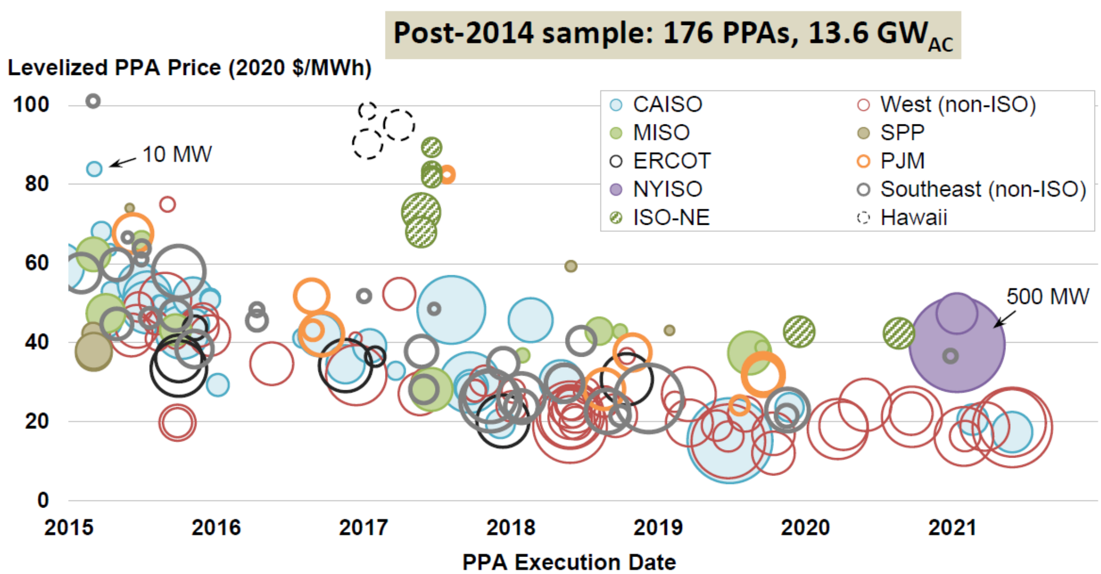
2. Electrolysis

There are several factors that control the economics of green hydrogen. This is really a production method, not a form of hydrogen. The molecules of hydrogen are the same whether it is grey hydrogen (made from natural gas), blue hydrogen (ditto, but the carbon dioxide emitted by this process is captured and sequestered) or green hydrogen (made from water using renewable electricity to disassociate the hydrogen and oxygen via electrolysis). Thus the main consumable (from a cost standpoint) used to produce green hydrogen is renewable electricity, and it is one of the main contributors to the cost of the green hydrogen.

2.1. Renewable Electricity Cost

Most that have been paying attention know that the cost of renewable electricity has been declining rapidly. Thus the economics for green hydrogen has been pretty poor until recently, and is still only marginal, but trending in a good direction. As of 2020, green hydrogen was still 2-3 times more expensive than blue hydrogen. However some components of the price of green hydrogen are low enough that *in the best-case scenario, green hydrogen can already be produced at costs competitive with blue hydrogen today, using low cost renewable electricity, i.e. around USD 20 per megawatt-hour (MWh).*[2]

Note from the chart below that the cost of renewable electricity, based on actual power purchase agreements throughout the U.S., is already at or below $20/MWh for large utility-scale PV projects (100 to 400 MW) in the Western U.S.[3]



Thus we are currently entering a transition to where some green hydrogen applications will start to approach economic viability.

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[2] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi, 2020, https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[3] Mark Bolinger, Joachim Seel, Cody Warner, and Dana Robson, Lawrence Berkeley National Laboratory, “Utility-Scale Solar, 2021 Edition,” Octorber 2021, https://emp.lbl.gov/sites/default/files/utility_scale_solar_2021_edition_slides.pdf

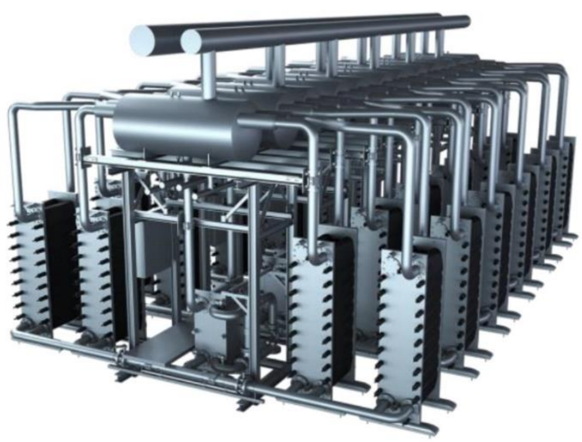
2.2. Electrolyzer Cost

Low electricity cost is not enough by itself for competitive green hydrogen production, however, and reductions in the cost of electrolysis facilities are also needed. This is the second largest cost component of green hydrogen production and is the focus of this report, which identifies key strategies to reduce investment costs for electrolysis plants from 40% in the short term to 80% in the long term. These strategies range from the fundamental design of the electrolyzer stack to broader system-wide elements, including: [2]

- ***Electrolyzer design and construction:*** *Increased module size and innovation with increased stack manufacturing have significant impacts on cost. Increasing the plant from 1 MW (typical today) to 20 MW could reduce costs by over a third…*

Author's comment & added information: Note that relative to the bullets above and below, the figure below is Siemens latest electrolyzer array. *The company was preparing for gigawatt production of its Silyzer 300 PEM electrolyzer arrays, each array comprising 24 modules with a combined 17.5 MW input capacity… Siemens Energy is targeting renewable hydrogen costs of $1.50/kg by 2025 based on a power cost of $16/MWh and a 100 MW electrolysis system running for 6,000 hours a year… The company expects its electrolyzer project portfolio to increase tenfold every four to five years with a first 100 MW Next Gen Silyzer targeted for 2023.* [4]

Siemens Silyzer 300 Electrolyzer Module Array



- ***Economies of scale:*** *Increasing stack production to automated production in GW-scale manufacturing facilities can achieve a step-change cost reduction. At lower manufacture rates, the stack is about 45% of the total cost, yet at higher production rates, it can go down to 30%. For Polymer Electrolyte Membrane (PEM) electrolyzers, the tipping point seems to be around 1 000 units (of 1 MW) per year, where this scale-up allows an almost 50% cost reduction in stack manufacturing…*[2]

[4] Andreas Franke, S&P Global, "Siemens Energy targets $1.50/kg renewable hydrogen cost by 2025," March 2021, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/032221-siemens-energy-targets-150kg-renewable-hydrogen-cost-by-2025

- ***Procurement of materials:*** *Scarce materials can represent a barrier to electrolyzer cost and scale-up. Current production of iridium and platinum for PEM electrolyzers will only support an estimated 3 GW-7.5 GW annual manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030. Solutions that avoid the use of such materials are already being implemented by leading alkaline electrolyzer manufacturers, however, and technologies exist to significantly reduce the requirements for such materials in PEM electrolyzers. Anion Exchange Membrane (AEM) electrolyzers do not need scarce materials in the first place.*

- ***Efficiency and flexibility in operations:*** *Power supply represents large efficiency losses at low load, limiting system flexibility, from an economic perspective. A modular plant design with multiple stacks and power supply units can address this problem.*

  Compression could also represent a bottleneck for flexibility, since it might not be able to change its production rate as quickly as the stack. One alternative to deal with this is an integrated plant design with enough capacity to deal with variability of production through optimized and integrated electricity and hydrogen storage.

2.3. Virtual Circle

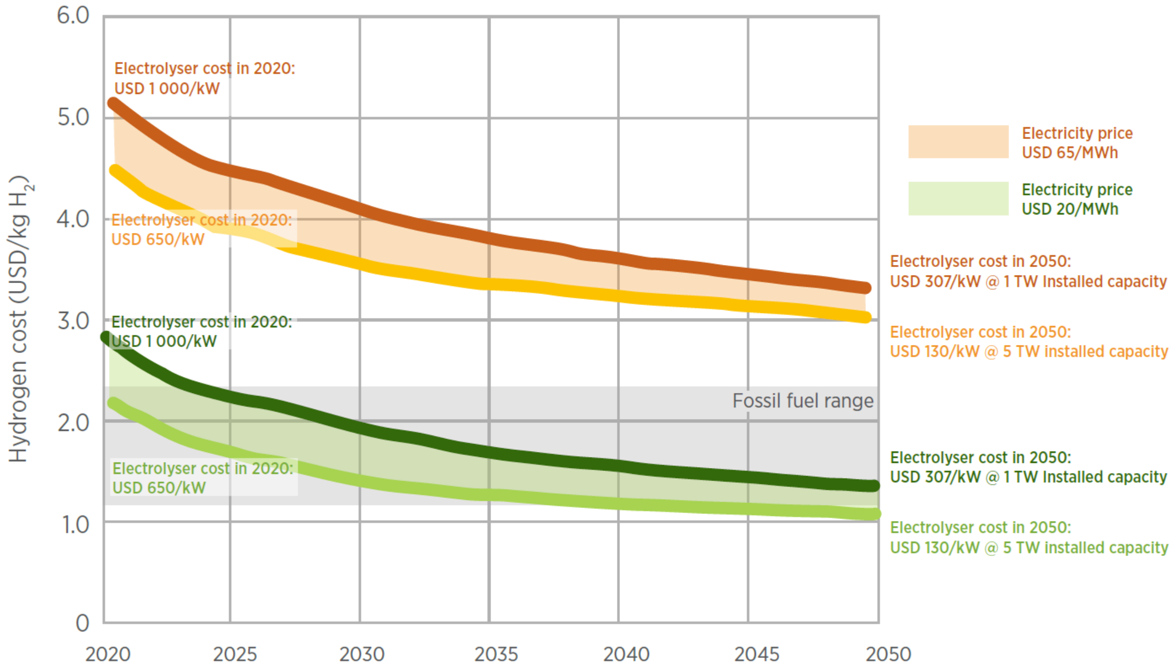
Green hydrogen production can provide significant flexibility for the power system, if the value of such services is recognized and remunerated adequately. Where hydrogen will play a key role in terms of flexibility, as it does not have any significant alternative sources to compete with, will be in the seasonal storage of renewables. Although this comes at significant efficiency losses, it is a necessary cornerstone for achieving 100% renewable generation in power systems with heavy reliance on variable resources, such as solar and wind.

Author's comment: The term "seasonal" storage in the above text is a bit misleading. Current technology mainly uses 4-hour storage at rated output using batteries. This works really well in my home-state (California) when paired with PV, but not so much with wind, which can have low-wind events that last for many days to more than a week during our peak demand period (late spring to early-autumn). Longer range electrochemical storage (using flow-batteries, for instance) can help with this by offering eight- to twelve-hour storage, but not really solve it. Green-hydrogen-based storage could provide days-to-weeks of storage, which would mightily mitigate this problem.

In areas that are leaders in the transition to clean energy (in the west), we are already seeing early adapters start pilot projects. Eventually these will scale up in the size and number of projects, thus increasing the volume of green hydrogen production and driving down the cost of green hydrogen. More applications / areas will adapt green hydrogen technologies in lieu of present GHG-producing technologies, driving further technical advances and economies of scale in a virtual-circle.

This is similar to the development process that photovoltaic generation followed, and that eventually resulted in the economics shown above.

The chart below from reference 2 gives the overall price of green hydrogen based on several parameters.



3. Fuel Cell Pricing

The article referenced below is by Ballard, one of the oldest and largest manufacturers of PEM fuel cells (since 1986). One might argue that it is in their best interest to promote fuel-cells, but on the other hand, who else knows enough about fuel cell technology and economics to make a credible estimate of future pricing?

Even with limited production volume, the price of fuel cell vehicles—especially buses—has been reduced by 65% over the past 10 years.[5]

What has driven this price reduction?

On the fuel cell itself, major gains to date have been driven by innovations in technology and product improvements. With decades of experience, Ballard has been able to deliver these gains in combination with industry leading durability and reliability.

An excellent example of this is Ballard's eighth generation fuel cell power module. The recently launched FCmove™ reduced product total life cycle costs by 35% compared to the previous generation. In fact, with each new generation, we've consistently reduced the cost by more than a third.

Additionally, there are a number of other elements that have contributed to the overall cost reduction of fuel cell electric vehicles including:

- *Reduced price of the hydrogen storage tank*
- *Reduced price and improved integration of the vehicle's electric powertrain*
- *Fuel cell-battery hybridization of the vehicle—combining a smaller fuel cell with lithium batteries, whose price has also been falling…*

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[5] Nicolas Pocard, Ballard Blog, "Fuel Cell Price to Drop 70-80% as Production Volume Scales," Feb 11, 2022, https://blog.ballard.com/fuel-cell-price-drop

According to the McKinsey Study, "a cost reduction of roughly 70-80% for fuel cell vehicles would be possible given an annual production volume of 150,000 vehicles".

Similar reductions could also be reached for the PEM stack and the fuel cell balance of plant. Manufacturers could capture significant fuel cell cost reductions of approximately 60-65% with even relatively small annual production volumes of 10,000 trucks per year.

This is in line with the Deloitte-Ballard report's findings. We're confident we can reduce the price of the fuel cell system to be competitive with diesel engines, and meet the US Department of Energy targets of less than $100/kW for annual production of over 150,000 systems/year.

Such cost reductions will be driven mainly by industrialization of the fuel cell system, because unlike batteries, fuel cells have a relatively low dependency on commodities. Instead, fuel cell systems are produced mainly from carbon, steel, and aluminum manufactured parts…

4. Other Generation Methods

Currently aero-derivative combustion turbines can be modified to use 100% hydrogen fuel. See section 2.3 of the earlier post linked below. For applications that require either a large amount of power and/or a lower capital cast than fuel cells can currently provide, these are a reasonable fit.

https://energycentral.com/c/gn/reasonable-transition

5. Specific Applications

In this section we will just look at the applications that will require the highest volume of green hydrogen. The first two applications below are already starting to appear, and these seem to have a strong need for a fuel that does not emit greenhouse gases (verses an energy-storage method).

5.1. Hydrogen Rail (Hydrail)

Most lower-volume commuter rail systems and all freight systems currently use some form of diesel-electric propulsion. California Executive Order (EO) N-79-20 sets a target that all off-road vehicles and equipment will be zero-GHG operations by 2035. Note that off-road vehicles includes all rail vehicles – commuter and freight. Currently commuter rail systems in California that are being built or upgraded and are not fully electrified are making a commitment to use rolling stock that is fueled by green hydrogen.[6]

Commuter rail is mostly used in California's major metropolitan areas, and the peak commute times run from 5:00 AM to 9:00 AM in the morning and 3:00 PM until 7:00 PM in the afternoon to evening. During these times rolling stock must be operated continually, and thus battery powered rolling-stock is a non-starter. The volumes used by these systems justify a large on-site hydrogen production and storage system.

The early deployment of Hydrail by commuter rail systems will develop both the volume of green hydrogen production and the storage, refueling and fuel-cell technology required to bootstrap freight-rail into Hydrail conversion.

[6] See https://energycentral.com/c/ec/hydrail

5.2. Commercial / Industrial Backup and Peaking

California has expensive retail power. California hates diesel engines. Many of the large companies that call California home, are obliged to be environmentally sensitive. You put all of these together and we are starting to see early adapters replace their diesel back-up electricity fleets with distributed fuel cell power (see earlier post linked in the Introduction).

Also diesel emergency back-up generation is legally limited as to when it can be used. Fuel-cells can be used to offset peak-power pricing (diesels cannot).

Most current diesel back-up generators are contained in a separate building away from other buildings, and close to the site's electric intertie for a number of reasons (fuel storage, noise, emissions). There is a low-cost way to directly replace these buildings that can be seen in section 4 above (using hydrogen-fueled turbines), and this method retains the ability to offset peak power. Distributed power using fuel cells is more efficient, but requires significant infrastructure upgrades.

5.3. Major Logistics Hub

A major logistics hub is an area near a major metropolitan area where the following conditions exist:

- Near major highways, rail lines and air-transport centers
- Reasonable property values
- Reliable utilities (including Internet connections)
- Large population with relatively low-cost labor
- An accommodating regional government

I've lived in Northern California most of my adult life, most of it in the Livermore Valley. I know the primary logistics hub for my region is just east of Livermore, because I drive through it every week or two going from Livermore to our mountain home in the Sierras:

Thanks to its strategic transportation access points within the Northern California Megaregion,[7] San Joaquin County is expanding its reputation as the premier setting for corporate warehouse and logistics, especially in Lathrop and Tracy. The presence of a deep-water port and a cargo-centric airport in Stockton help make San Joaquin even more attractive for the industry.[8]

I would guess that many other large "megaregions" have similar logistics hubs. Certainly I know that Southern California probably has two or three of these, but let's focus on the one I know about, and have written about.[9]

[7] The Northern California Megaregion is composed of 21 counties grouped into four regions: Bay Area, Sacramento Area, Northern San Joaquin Valley, and Monterey Bay Area. It boasts one of the fastest growing economies in the country, joining the Texas Triangle and Gulf Coast as the only three megaregions to grow their gross regional product (GRP) at a compound annual rate greater than 5.0% since 2010. The population of the Northern California Megaregion is 12.7 Million. http://www.bayareaeconomy.org/files/pdf/The_Northern_California_Megaregion_2016c.pdf

[8] San Joaquin Council of Governments, "Warehousing and Logistics – Industry Overview," https://www.sjcog.org/389/Warehousing-and-Logistics

[9] See subsection 2.9 of the earlier post: https://energycentral.com/c/ec/2021-electric-truck-bus-update-part-1-trucks

First of all in reference 9, I identified 24 major logistic / fulfillment / warehousing centers in San Joaquin County (more have been built since I posted this). Many of these have freight railroads adjacent to them, and thus there will be a strong need for Hydrail refueling depots in the future (by 2035). Given this, and these centers need for:

- Backup power
- Low-cost power for peak-reduction
- Some cross-country trucks (shorter-distance trucks will use battery-electric power, but as you leave our megaregion and head east it's a long way to the next major metro area).

Thus it might make sense to build several really large green hydrogen production facilities in San Joaquin County with hydrogen distribution networks.

5.4. Utility-Scale Hydrogen Energy Storage Facility

California has about 30 existing combined cycle electric generation plants that are currently fueled by natural gas. But they also emit large amounts of greenhouse gases (GHG). Converting them to burn hydrogen would reduce their emissions of GHG to very near zero. For at least some of them this should be possible by 2030. See sections 2 and 3 of the post linked in section 4 above.