Energy Supply and Conversion 39-610

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Topic **Green Chemical Storage: Hydrogen and Ammonia** **Group 11**

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a. Introduction to Hydrogen and History

Hydrogen is both the lightest and most abundant element in the universe and on Earth (1). It is mostly found in compounds containing other elements, such as hydrocarbons or water (H_2O). It can also exist in a flammable and gaseous diatomic form (H_2), or even a liquid diatomic form at temperatures below 20K.

Hydrogen has been used for various purposes over history. It was first identified by Philippus von Hohenheim in the 1500's by dissolving metals in sulfuric acid (2). One of its first applications was in balloons due to its lower density than air, including the infamous Hindenburg which crashed in 1937. In 1789, electrolysis of water was used for the first time to produce hydrogen. The idea of a fuel cell, which converts hydrogen back to electricity was introduced in 1801. Practical fuel cells did not appear until much later in 1959. Another significant use, the Haber-Bosch process for making ammonia (NH_3) out of hydrogen was invented in 1910. Nowadays, we mostly use hydrogen for ammonia, oil refining, and steel production.

Hydrogen is gaining appeal for its potential to serve as an energy carrier. The chemical energy in hydrogen gas is about 33.6 kWh per kg of H_2. By weight, hydrogen gas has the highest energy density of any common fuel, although its energy density by volume is quite low. The low energy density by volume can make transportation less cost-effective, so ammonia has been suggested as a carrier for hydrogen since it has a much higher boiling point and could be transported as a liquid. Given the recent efforts to drive decarbonization, perhaps the most appealing aspect of hydrogen is that there are no CO_2 emissions associated with recovering energy from it (via combustion/oxidation) since unlike most fuels, it contains no carbon. Hydrogen can be produced with electricity via electrolysis and then stored or transported until it is needed. Both fuel cells and gas turbine engines present opportunities to recover energy from hydrogen in the form of electricity.

b. Colors of Hydrogen and Methods of Production

Very little hydrogen is sourced from geologic formations. Instead, various processes exist to turn different feedstocks into hydrogen gas. Hydrogen is categorized based on the method of production and the feedstock/energy source used. Each method of production is designated as a 'color.' Table 1 summarizes the different colors of hydrogen.

Table 1. "Colors" of Hydrogen and how they are produced (3,4).

Color	Feedstock	Process	Relative CO_2 Emissions
Black Hydrogen	Bituminous Coal	Gasification	High
Brown Hydrogen	Lignite Coal	Gasification	High
Grey Hydrogen	Methane	Steam Methane Reforming (SMR)	Medium
Blue Hydrogen	Methane	SMR with Carbon Capture and Storage (CCS)	Low-Medium
Turquoise Hydrogen	Methane	Pyrolysis	Low
Green Hydrogen	Water, Electricity from Renewables	Electrolysis	Low
Pink Hydrogen	Water, Electricity from Nuclear	Electrolysis	Low
White Hydrogen	Natural Geologic	N/A	-

	Hydrogen Sources		

All of the types of hydrogen in Table 1 have seen some level of deployment at scale, except Turquoise Hydrogen, which is still in an experimental phase. The pyrolysis process for turquoise turns methane into elemental carbon and hydrogen gas in the absence of oxygen, theoretically with no emissions of CO_2.

Gasification Process: Black and Brown Hydrogen

This process involves exposing coal to oxygen and water vapor while heating it (5). The product is hydrogen gas and carbon monoxide (a mixture called syngas). The syngas can be purified to get a hydrogen gas product. The reaction for gasification is:

$$3C + O_2 + H_2O \rightarrow H_2 + 3CO$$

Carbon monoxide can also further react with water vapor to produce carbon dioxide and more hydrogen gas:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Steam Methane Reforming (SMR): Grey and Blue Hydrogen

SMR is the most common method of producing hydrogen in the world. It involves using methane and water vapor as a feedstock (6). The SMR overall reaction:

$$CH_4 + H_2O \rightarrow 3H_2 + CO$$

CO may continue to react with water vapor to form CO_2 and more hydrogen (the water gas shift reaction).

$$CO + H_2O \rightarrow CO_2 + H_2$$

The carbon dioxide produced by the shift reaction may then be separated, transported, and stored.

Electrolysis of Water: Green and Pink Hydrogen

This process splits water into hydrogen and oxygen gas. A cathode and anode in an electrolytic cell are utilized to achieve this. The electrodes are most often made from platinum, and nickel electrodes can also be used for alkaline cells. Electrolysis makes use of voltage applied across the water, which needs to be at minimum 1.23V. Electrical power supplies this voltage (7,8,9). The overall reaction is:

$$2\,H_2O(l) \rightarrow 2\,H_2(g) \;+\; O_2(g)$$

Reduction at the cathode produces hydrogen gas, and oxidation at the anode produces oxygen gas. The half reactions depend on the pH in the electrolyte. In acidic conditions, the half reactions are:

Cathode (reduction): $2H^+(aq) + 2e^- \rightarrow 2H_2(g)$

Anode (oxidation): $2\,H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

In basic conditions, the half reactions are:

Cathode (reduction): $2\,H_2O(l)\ +\ 2e^{-} \rightarrow H_2(g)\ +\ 2OH^{-}(aq)$

Anode (oxidation): $2OH^{-}(aq) \rightarrow 0.5\,O_2(g)\ +\ H_2O(l)\ +\ 2e^{-}$

The type of electrolyzer which uses basic conditions is called an Alkaline electrolyzer, and the type which uses acidic conditions is called Proton Exchange Membrane (PEM) electrolysis .

A diagram of electrolysis is shown in Figure 1.

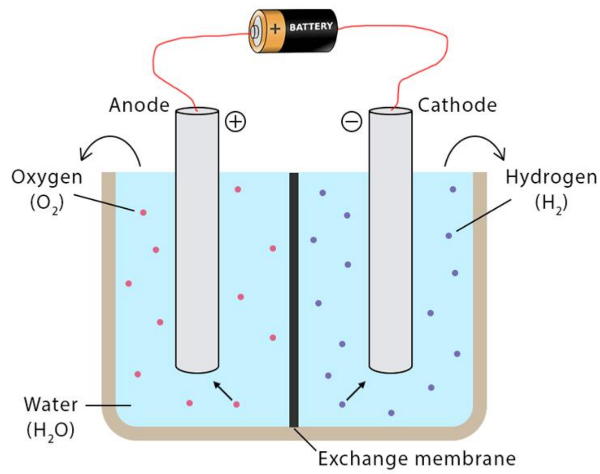


Figure 1. Diagram of electrolytic cell for water electrolysis. Source: Chemistry Learner (9).

There are inefficiencies associated with converting electrical energy to chemical energy in hydrogen. A ton of hydrogen can release up to 33.6 MWh of heat when combusted, but about 48MWh of electricity is required to produce the hydrogen with the best available electrolysis technology (10).

c. Hydrogen Resource Overview

The color spectrum of hydrogen is evermore expanding. However, what this wheel fails to encapsulate is total production that each hydrogen spectrum accounts for in our energy mix. According to Table 2, the hydrogen production wheel is dominated by fossil fuel based hydrogen which includes Black, Brown, Grey, and Blue hydrogen.

Table 2. Global hydrogen production in 2022 (Source: IEA) (11). Total 95 million tons production.

Energy Source/Production Method	Percent of Production
SMR (Grey Hydrogen)	62
Coal (Black/Brown Hydrogen)	21
As an Industrial By-Product	16
SMR with CCUS (Blue Hydrogen)	0.6
Oil	0.5
Electrolysis (Green/Pink Hydrogen)	0.1

The reserves for white hydrogen are largely unknown, as grey and black hydrogen have traditionally been much more popular. However, recently, a 46 million ton formation was found in France (12).

The hydrogen resource using these production methods is finite and depends on the total reserves of Coal for gasification and Natural gas for SMR. The fossil fuel derived hydrogen resources are limited by the reserves of the fossil fuel in question. For SMR, about 3.4 kg CH4 is used per kg H2, and for coal gasification, 8 kg Coal is used per kg H2 (13,14). To estimate the effective reserve of fossil hydrogen, we can estimate the total reserve of coal and natural gas, and then calculate the percentage of global natural gas consumption that is used for hydrogen production and repeat the process for coal. Since coal and gas represents the majority of our hydrogen mix as well as incorporating blue, gray, brown and black hydrogen on the spectrum, it is helpful to know how much of the resource we can tap into using SMR and coal gasification. Table 3 shows the available resource for coal and natural gas dedicated to hydrogen production globally and the equations used to calculate this are detailed below.

$$x, y = \frac{natural\ gas/coal\ used\ for\ H2\ production}{total\ global\ consumption\ of\ natural\ gas/coal} = \%\ of\ natural\ gas\ or\ coal\ consumed\ for\ hydrogen\ production$$

$$Reserves\ of\ grey + blue\ hydrogen = x(total\ natural\ gas\ reserves)$$

$$Reserves\ of\ brown + black = y(total\ coal\ reserves)$$

$$methane\ to\ hydrogen\ conversion\ rate = \frac{3.4KgCh4}{1KgH2}$$

$$coal\ to\ hydrogen\ conversion\ rate = \frac{8KgCoal}{1KgH2}$$

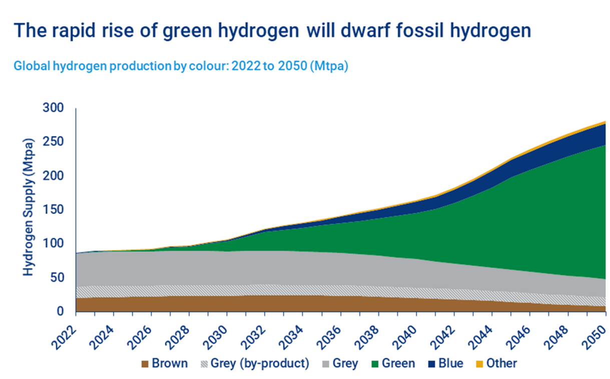
$$t = \frac{total\ global\ reserve\ of\ coal\ or\ natural\ gas}{natural\ gas\ or\ coal\ consumption\ for\ H2\ production} = time\ for\ reserve\ to\ run\ out$$

Table 3. Reserves for Fossil-derived Hydrogen Resources. Natural Gas and Coal reserves from EIA.

Black + Brown Hydrogen	Coal Proven Reserve (Tonne Coal)	Fraction of coal used for hydrogen production	Coal used for hydrogen production (Tonne Coal)	Number of years of reserve	Hydrogen proven reserve TWh
	20200000000	0.01922	159600000	126.5664	161600
Blue + Grey Hydrogen	Natural Gas proven reserve (Kg CH4)	Fraction of natural gas used for hydrogen production	Natural gas used for hydrogen production (Kg CH4)	Number of years of proven reserve	Hydrogen proven reserve TWh
	1.106E+13	0.075	2.138E+10	517.243	129033.33

Theoretically hydrogen is an infinite resource as hydrogen combines with other elements to create most compounds (namely water). Figure 2 shows the trend we can expect as green hydrogen methods and technologies become more widely adopted. While we won't run out of hydrogen we will begin to see a rapid transition to green hydrogen. At the same time black, brown, gray and blue hydrogen will be phased out. While it may appear that water resource and cost is our only limit to hydrogen production capacity, there are other bounds we have that limit green hydrogen production as we proceed with scaling up efforts. It is unclear when the tipping point in the price of production for green hydrogen will become cost competitive with other hydrogen sources on the spectrum (as a fuel); much even

Figure 2.



more uncertain is when it will become cost competitive with fossil fuels. In fact Irena predicts that the falling renewable power cost and falling capital cost for electrolyzers is creating an economic case for green hydrogen IRENA sees a global economic potential for 19 exajoule (EJ) of hydrogen from renewable electricity in total final energy consumption by 2050 (15).

An analysis can be done on electrolysis methods to decipher the total resource available to us in the near future as we transition from a gray hydrogen dominant hydrogen mix to a green hydrogen dominant mix. The total theoretical energy resource potential on earth assuming that all freshwater on earth can be converted to hydrogen is practically infinite as shown in Table 4, and assuming an energy density of 33.6 KWh per kg of hydrogen (16). Realistically only 33% of this freshwater is allocated to energy production representing technically feasible potential. As green hydrogen production is not economically viable compared to fossil hydrogen at this time for any technology this number is not reported. Installed capacity is based on the 3GW electrolyzer capacity which further bounds our pure green hydrogen output assuming 1GW of electrolyzer produces 0.15 million tons of hydrogen (17). It is important to understand that this 3GW electrolyzer will be scaled up very rapidly in the next decade. The future for hydrogen is very promising if we can scale up electrolyzing capacity to Net Zero Production recommendations of 560GW representing 9-15 exajoules of green energy production which is on par with the Irena predictions of 19 exajoules of green energy consumption by 2050.

Table 4. Theoretical and Feasible potential for Green Hydrogen Resources and Current Installed Electrolyzer Capacity.

	KWh	MWh	Exajoule
Theoretical Potential (fresh water on earth)	1.5344E+20	1.5344E+17	5.52E+08
Technically Feasible Potential (% of freshwater for energy)	5.11467E+19	5.11467E+16	1.84E+08
Economically Feasible Potential	-	-	-
Installed Capacity in 2023 (3GW electrolyzer capacity)	13468950000	13468950	0.0484843
Production in 2019	462000000	462000	0.0016631

d. Hydrogen Conversion and Consumption

Hydrogen is critical to several industries and also has an important advantage in that its combustion does not release CO_2.

$$2H_2 + O_2 \rightarrow 2H_2O + Energy$$

Hydrogen gas has many applications. The current three largest end uses of hydrogen by far are metals, fertilizer, and petroleum refining. Hydrogen is used in metal treating and production for various steps including sintering, annealing, and brazing. Hydrogen can be used as a reducing agent in metal production and also as a source of high temperature heat, replacing natural gas, syngas, or coke, which produce CO_2 when combusted. Fertilizer production makes use of the Haber Bosch process, which uses hydrogen and nitrogen as feedstocks to form ammonia. Petroleum refineries can use hydrogen gas to lower the sulfur content of oil by converting it to H_2S. Other petrochemical and hydrocarbon production processes make use of hydrogen as well, such as for producing unsaturated fats and oils (18-21).

Hydrogen may also be used to produce electricity. There are two ways to accomplish this. First, a traditional gas turbine may be used. Many newer gas turbines can run on hydrogen in addition to methane to power a Brayton Cycle. For example, new GE gas turbines can run on 5-100% hydrogen (22). At first glance, this method of electricity production may not make much thermodynamic sense if the hydrogen was produced with electrolysis, since electricity would simply be converted back to electricity. However, the advantage in this use of hydrogen is that excess green electricity may be stored in the form of hydrogen, and then converted back later during higher demand with a gas turbine.

The alternative way to make use of hydrogen in electricity production is hydrogen fuel cells. An electrochemical cell can be used to convert hydrogen and oxygen into water.

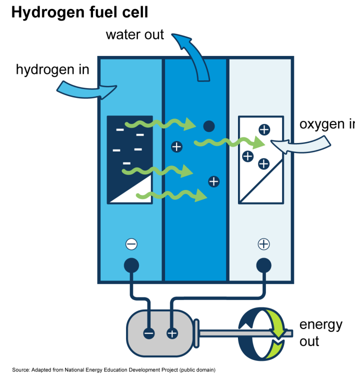


Figure 3. Hydrogen Fuel Cell Diagram. Source: EIA (20).

Hydrogen fuel cells can go into a variety of uses, such as spacecraft, vehicles, and computers. Hydrogen fuel cell vehicles are available in California and Hawaii, but refueling stations have limited availability. In fact, there are only 56 in total in the US. Given the limited progress of hydrogen fuel cell vehicles and the already exploding popularity of EVs, it is not likely that fuel cell vehicles will gain significant market penetration. Various kinds of hydrogen fuel cells have been developed, including alkaline as well as high temperature solid oxide and molten carbonate fuel cells. Alkaline fuel cells, invented in 1959, were used in the Apollo flights and require a temperature around 375K. Other high temperature fuel cells may require temperatures over 900K, which represents a significant complication for materials use and operation. Fuel cell power plants currently exist in the US, totaling to 350 MW nameplate capacity. However, all of the 147 facilities use methane, landfill gas, or biogas instead of hydrogen. Therefore, utility scale hydrogen fuel cell electricity production is still an unproven concept.

Hydrogen is useful as a source of heat when combusted. It could technically serve for low temperature heating of homes and other buildings as an alternative to combusting natural gas, but heat pumps have been a more effective use of renewable electricity (19,23). Instead, hydrogen can be used as an excellent source of high temperature heat. Hydrogen can burn in air to a temperature of about 2300K (24). This makes hydrogen an excellent opportunity to displace other high temperature heat sources, like combustion of natural gas and coal, for needs such as in steel and aluminum production.

Another attractive feature of hydrogen is its ability to serve as a means of energy storage. During periods of excess electricity production, hydrogen can be produced and then converted to electricity or heat when needed. Hydrogen itself can be stored in either a gaseous or liquid form. Gaseous hydrogen can be stored in tanks, pipelines, or in geologic formations like salt caverns. This is the most common phase in which hydrogen is stored. The alternative is liquifying hydrogen at 20K, and transporting/storing it in cryogenic tanks. This process is extremely energy intensive and is not done very often.

Hydrogen may also be stored as part of a different chemical compound. Ammonia produced from hydrogen via the Haber-Bosch process is the most popular choice. A cracking process can be used on ammonia to convert it back to hydrogen and nitrogen (10). There are some issues with using ammonia, namely that the Haber-Bosch process requires high temperatures and therefore high energy demand. Ultimately, around 20 MWh per ton of hydrogen is needed to turn it into ammonia, compared to the 33.6 MWh chemical energy per ton in hydrogen. On the other hand, ammonia is much easier to liquify at 240K and therefore its transport is much simpler than hydrogen. There will also be less energy loss during storage for liquid ammonia than liquid hydrogen due to having a temperature closer to ambient.

e. Hydrogen Capacity and Facilities in China and the World

According to the International Energy Agency (IEA), for 2022, global hydrogen consumption was 95 million metric tons. China represents the largest share of this consumption, followed by North America and the Middle East.

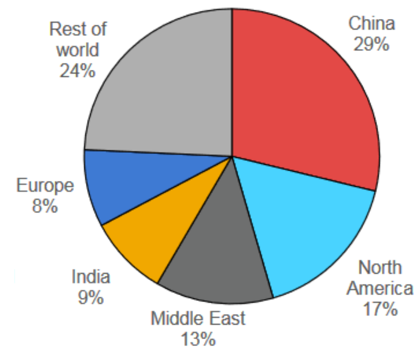


Figure 4. Hydrogen Use By Region, 2022. Source: International Energy Agency (11).

As of 2022, the vast majority of hydrogen consumption is either for industrial use or refining. The IEA predicts that for a net zero by 2050 scenario, hydrogen consumption will increase to about 150 MT/yr by 2030, with about 45 MT/yr of this consumption for transport, synfuel, and power generation.

Hydrogen production was also approximately 95 million tons in 2022. The breakdown of types of hydrogen produced in 2022 is shown in Table 2. It highlights that the vast majority of hydrogen is not low emission (99.4%).

The green hydrogen production depicted in Table 2 corresponds to about 100,000 tons of green hydrogen per year global capacity. As of 2022, most of this capacity is in North America.

The current US production of hydrogen is about 10 MT per year, of which 95% is made with SMR (gray or blue hydrogen) and only ~1% is from electrolysis (green or pink hydrogen). The Inflation Reduction Act (IRA) of 2022 is expected to promote the expansion of green hydrogen production in the US (25,26). The US offers several tiers of subsidies depending on the emissions associated with the hydrogen. Projects are eligible for subsidies only if they include installation of new low emission and clean electricity.

China is currently the world's largest producer and user of hydrogen. The total hydrogen consumption in China is 34.7 million tons per year, and over 99.9% of hydrogen consumption in China is for industrial uses (27). Most of the hydrogen produced in China is fossil (black/brown/gray) hydrogen. The breakdown of hydrogen production in China in 2021 is shown in Table 5.

Table 5. Hydrogen Production in 2021 in China (27).

Hydrogen Type	Production (tons/yr)
Black/Brown	19,590,000
Grey	7,730,000
Green	17,000
As an Industrial By-Product	6,400,000
Total	36,480,000

It should be noted that green hydrogen only makes up some 0.05% of total hydrogen production in China as of 2021.

There has been recent interest in expanding green hydrogen production in China to meet the country's needs while producing much less emissions than gray or blue hydrogen. The Chinese government has announced a target of producing 100,000 to 200,000 tons of green hydrogen a year by 2025 (about 0.25-0.5% of production), corresponding to a 1-2 million tons per year CO_2 reduction in emissions. Sinopec, a Chinese state-owned petrochemical company, recently started operation of a new green hydrogen facility in Kuqa City, Xinjiang in July of this year. Specifications of the new facility are shown in Table 3. An additional facility by Three Gorges in Narisong, Inner Mongolia also started up in 2023. Furthermore, there is another Sinopec facility under construction in Ordos, Inner Mongolia.

Table 6. Specifications of recent and upcoming Green Hydrogen Facilities in China. Data omitted when not known (28,29).

Facility	Production Capacity (tons/yr)	Electricity Source	Storage Capacity (m^3)	Transmission Capacity (m^3/hr)	Capital Expense ($M)
Kuqa (2023)	20,000	Solar PV	210,000	28,000	414
Narisong (2023)	10,000	Solar PV	-	-	-
Ordos (Upcoming)	30,000	Wind and Solar PV	288,000	-	-

The new facilities and existing green hydrogen capacity puts China already on track to meet about half of its goal for 2025.

Concerns have been raised about Kuqa facility and its ability to meet capacity using only the Solar PV in the facility. According to BloombergNEF, its 361 MW solar farm could only meet 58% of the energy needs at maximum capacity. Therefore, Sinopec would need to buy energy from the grid. If they cannot source renewable/low emission energy, then they may have to rely on fossil electricity.

There are countless other green hydrogen facilities under construction or planned all around the world for the next two decades. According to the IEA, there are over 400 GW of announced green hydrogen projects, compared to approximately 2.2 GW of existing projects. Most of these projects are still in early stages of development or in feasibility studies. One notable example of an upcoming facility is the NEOM Green Hydrogen Project in Saudi Arabia, set to start up in 2026 (30). It is a joint venture among NEOM, Air Products, and ACWA Power. It will have a capacity of around 220,000 tons of hydrogen per year, powered by 4 GW of solar PV and wind. The facility also has a capacity of 1.2 million tons of ammonia per year, which allows all the hydrogen produced to be stored in an easily transportable form.

f. Political, economic, social benefits / concerns of Hydrogen

The economics of hydrogen production are important to consider, as shown in Figure 5. SMR and coal gasification are mature technologies, and yield quite low costs for hydrogen ($1-2 / kg). Blue hydrogen adds some cost on the order of an additional $1/kg hydrogen compared to SMR.

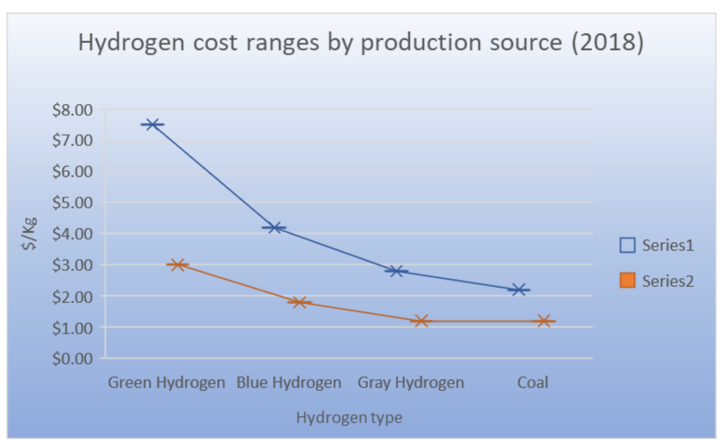


Figure 5. Hydrogen cost ranges by production source. (31)

According to the hydrogen cost ranges provided by the IEA, green hydrogen is the most expensive way to produce hydrogen. This is due to the high cost of renewable electricity, but it is also dependent on the cost of electrolyzers (32). It should also be mentioned that large scale green hydrogen is not as mature a technology as fossil hydrogen.

The levelized cost of hydrogen through electrolysis depends on several factors, including the price of the electrolyzer, its utilization rate, and the electricity cost during operation. This dependence can be seen in figure 6 below. When the electrolyzer is used more frequently, it lowers the proportion of capital costs, meaning the

Electrolyzer/Capital Expenditure (Capex) associated with the electrolyzer in the total hydrogen production expenses. However, higher utilization also leads to increased electricity expenses because the electrolyzer is operating during hours of costly electricity. While you can't control the purchase price of electricity you can control the utilization during the hours when electricity is expensive and so there is an optimum utilization reducing the price assuming that most AEP and PEM electrolyzers have 70% efficiencies.

Alkaline (100 MW)

Energy Cost ($/MWh)	Electrolyzer Capex ($/kW)				
$/kg	$510	$570	$630	$690	$760
$10	$0.78	$0.82	$0.87	$0.91	$0.96
$20	$1.05	$1.09	$1.14	$1.18	$1.23
$30	$1.32	$1.36	$1.41	$1.45	$1.50
$40	$1.59	$1.63	$1.67	$1.72	$1.77
$50	$1.85	$1.90	$1.94	$1.99	$2.04

Alkaline (100 MW)

Energy Cost ($/MWh)	Electrolyzer Utilization				
$/kg	100%	90%	80%	70%	60%
$10	$0.87	$0.89	$0.95	$1.02	$1.12
$20	$1.14	$1.16	$1.22	$1.29	$1.39
$30	$1.41	$1.43	$1.49	$1.56	$1.66
$40	$1.67	$1.70	$1.76	$1.83	$1.93
$50	$1.94	$1.97	$2.03	$2.10	$2.20

Figure 6. Levelized Costs of Hydrogen for Green Hydrogen. (31)

Currently China is already leading the change in hydrogen production and currently has the most installed capacity (mostly from unabated fossil fuels) (33). It also has a strong market in the transportation sector for Fuel Cell Vehicles. It is also the country with the cheapest levelized cost of electricity. The economic feasibility is continuing a positive trend due to politics as the Chinese government has significantly increased government spending on hydrogen research and development. The Chinese government has also set targets to improve its green hydrogen to 100-200k tons/yr by 2025. This serves to support China's decarbonization and Chinese industries which rely on hydrogen. Also, the statewide subsidy program is available to support the development of fuel cell batteries. Moreover, China also plans to double its solar and wind generation capacity by 2030 which will further reduce green electricity prices in the region. This rapid transition and expansion of renewables will directly expand renewable based hydrogen.

It is also important to emphasize the environmental considerations of green hydrogen. Displacing millions of tons of fossil hydrogen per year will reduce CO_2 emissions by many million more tons per year. Given that China is currently the largest greenhouse gas producer in the world, green hydrogen provides an excellent opportunity to meet the needs of China's growing economy while abating emissions. On the other hand, green hydrogen will require significant capacity of renewable energy. This energy may not completely go toward displacing fossil energy if it is being used for hydrogen production instead. Additionally, wind and solar energy installations use a significant amount of land. They cannot be placed just anywhere, and could disrupt agriculture or force people to be displaced. China does have certain places, like Inner Mongolia, with empty land that could be used for green hydrogen power plants in order to get around such issues.

g. Policy and Pros/Cons of Hydrogen

Some of the cons of hydrogen involve issues of storage, distribution and the explosivity of hydrogen due to it being oxidizable and having high energy content. While hydrogen can be stored as a liquid or a gas, the liquid storage requirements for hydrogen requires very low temperatures at an astonishing -260°C to prevent reboiling due to the very high volatility of diatomic hydrogen (34). When in a gaseous form, it has very low volumetric energy density in gaseous state requiring very high pressures to maintain feasible energy density, another challenge is that hydrogen can leak easily from storage tanks.

These demanding storage requirements make distribution challenging as well. Hydrogen can be shipped, pumped through pipelines, or transported by ground. Pipeline infrastructure dedicated to hydrogen distribution is limited globally, especially in China, and it is reported that only 3 pipelines are operational spanning 100 km of hydrogen according to an International Energy Agency report (11). Hydrogen is often combined with nitrogen to create ammonia, increasing energy density and allowing easy distribution, however this ammonia if not used for fertilizers requires additional processing to revert back to pure hydrogen. The Energy demand for this haber-Bosch process is also quite significant as it requires very high temperatures. This reduces the overall efficiency of the process.

China has laid out a clear long term plan and progressive policy for increasing hydrogen production. This not only includes clear targets for hydrogen production but also a clear plan for scaling up electrolyzer production manufacturing for increased green hydrogen. China is already closing in on its near term stated goals for 100,000 tons/yr of green hydrogen by 2025. New and upcoming plants suggest that China will be able to significantly expand its green hydrogen capacity. Further investment and subsidies in renewable energy, electrolysis, and green hydrogen will allow China to succeed in decarbonizing hydrogen dependent industries like fertilizers and metal production.

Bibliography:

1. Hydrogen explained—U. S. Energy information administration(Eia). (n.d.). Retrieved October 3, 2023, from https://www.eia.gov/energyexplained/hydrogen/
2. Timeline of hydrogen technologies. (2023). In Wikipedia. https://en.wikipedia.org/w/index.php?title=Timeline_of_hydrogen_technologies&oldid=1177288012
3. The hydrogen colour spectrum| National Grid Group. (n.d.). Retrieved October 3, 2023, from https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum
4. The 9 colors and carbon impacts of hydrogen—U. S. Gain. (2022, January 10). https://www.usgain.com/resources/education-center/the-9-colors-and-carbon-impacts-of-hydrogen/
5. Hydrogen Production from Coal. (n.d.). www.HydrogenAssociation.org. Retrieved October 3, 2023, from https://www.mwcog.org/file.aspx?&A=6lJMMDOHmOUL2TT9fb7pcrAAeY5PdpMxMeZbS9eJzyo%3D
6. *Steam methane reforming*. (n.d.). Retrieved October 3, 2023, from https://studentenergy.org/production/steam-methane-reforming/
7. Hydrogen production: Electrolysis. (n.d.). Energy.Gov. Retrieved October 3, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis
8. Givirovskiy, G., Ruuskanen, V., Ojala, L. S., Lienemann, M., Kokkonen, P., & Ahola, J. (2019). Electrode material studies and cell voltage characteristics of the in situ water electrolysis performed in a pH-neutral electrolyte in bioelectrochemical systems. Heliyon, 5(5), e01690. https://doi.org/10.1016/j.heliyon.2019.e01690
9. Bhuyan, S. (2022, March 22). Electrolysis of water: Definition and equation. Chemistry Learner. https://www.chemistrylearner.com/electrolysis-of-water.html
10. Ammonia's role in a net-zero hydrogen economy. (n.d.). Kleinman Center for Energy Policy. Retrieved October 3, 2023, from https://kleinmanenergy.upenn.edu/research/publications/ammonias-role-in-a-net-zero-hydrogen-economy/
11. Global Hydrogen Review 2023. (2023). International Energy Agency (IEA). https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aaa175d/GlobalHydrogenReview2023.pdf
12. *World's largest white hydrogen deposit found in France*. (2023, September 15). World Economic Forum. https://www.weforum.org/agenda/2023/09/white-hydrogen-deposit-france/
13. Katebah, M., Al-Rawashdeh, M., & Linke, P. (2022). Analysis of hydrogen production costs in Steam-Methane Reforming considering integration with electrolysis and CO2 capture. Cleaner Engineering and Technology, 10, 100552. https://doi.org/10.1016/j.clet.2022.100552
14. Yang, Y., Wang, G., Lin, L., & Zhang, S. (2019). * Corresponding author: Yangym@cnis.ac.cn Analysis of Hydrogen Production Potential Based on Resources Situation in China. EDP Sciences. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj60fK81tqBAxX1lIkEHfgWBocQFnoECAgQAw&url=https%3A%2F%2Fwww.e3s-conferences.org%2Farticles%2Fe3sconf%2Fpdf%2F2019%2F44%2Fe3sconf_icaeer18_03021.pdf&usg=AOvVaw3QPRM9iEwmQBQKUN66K-66&opi=89978449
15. Unprecedented momentum for green hydrogen. (2019, October 10). https://www.irena.org/news/articles/2019/Oct/Unprecedented-momentum-for-green-hydrogen
16. Slanger, D. (2019, October 2). Run on less with hydrogen fuel cells. RMI. https://rmi.org/run-on-less-with-hydrogen-fuel-cells/
17. Hydrogen. (n.d.). Retrieved October 3, 2023, from https://www.lenntech.com/applications/hydrogen.htm#:~:text=Considering%20a%20very%20large%201,use%20per%20kilo%20of%20hydrogen).
18. Hydrogen for metal treating—Google search. (n.d.). Retrieved October 3, 2023, from https://www.google.com/search?client=firefox-b-1-d&q=hydrogen+for+metal+treating

19. Marocco, P., Gandiglio, M., Audisio, D., & Santarelli, M. (2023). Assessment of the role of hydrogen to produce high-temperature heat in the steel industry. Journal of Cleaner Production, 388, 135969. https://doi.org/10.1016/j.jclepro.2023.135969
20. Use of hydrogen—U. S. Energy information administration(Eia). (n.d.). Retrieved October 3, 2023, from https://www.eia.gov/energyexplained/hydrogen/use-of-hydrogen.php
21. Rambhujun, N., Salman, M. S., Wang, T., Pratthana, C., Sapkota, P., Costalin, M., Lai, Q., & Aguey-Zinsou, K.-F. (2020). Renewable hydrogen for the chemical industry. MRS Energy & Sustainability, 7(1), 33. https://doi.org/10.1557/mre.2020.33
22. Hydrogen-fueled gas turbines | ge gas power. (n.d.). Gepower-V2. Retrieved October 3, 2023, from https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines
23. Clark, S. (2020, March 21). Is hydrogen the solution to net-zero home heating? The Guardian. https://www.theguardian.com/science/2020/mar/21/is-hydrogen-the-solution-to-net-zero-home-heating
24. What is the typical flame temperature for different fuels? (n.d.). ThoughtCo. Retrieved October 3, 2023, from https://www.thoughtco.com/flame-temperatures-table-607307
25. Day, P., & Day, P. (2023, June 7). US grapples with how clean is green hydrogen. Reuters. https://www.reuters.com/business/energy/us-grapples-with-how-clean-is-green-hydrogen-2023-06-07/
26. Hydrogen production: Natural gas reforming. (n.d.). Energy.Gov. Retrieved October 3, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming
27. Bocca, R., Liu, W., & Zhu, S. (2023). Green Hydrogen in China: A Roadmap for Progress. World Economic Forum (WEF). https://www3.weforum.org/docs/WEF_Green_Hydrogen_in_China_A_Roadmap_for_Progress_2023.pdf
28. Sinopec's first green hydrogen plant starts production in Xinjiang. (2023, June 30). Reuters. https://www.reuters.com/business/energy/sinopecs-first-green-hydrogen-plant-xinjiang-starts-production-xinhua-2023-06-30/
29. Collins (l_collins), L., & Yihe (x_yihe), X. (2023, May 26). World's largest green hydrogen project—China's 260MW Kuqa facility—To be commissioned at the end of May. Hydrogen News and Intelligence | Hydrogen Insight. https://www.hydrogeninsight.com/production/world-s-largest-green-hydrogen-project-chinas-260mw-kuqa-facility-to-be-commissioned-at-the-end-of-may/2-1-1457242
30. Largest green hydrogen projects in the world. (n.d.). Retrieved October 3, 2023, from https://www.linkedin.com/pulse/largest-green-hydrogen-projects-world-futurefuels
31. *Levelized cost of energy+*. (n.d.). Https://Www.Lazard.Com. Retrieved October 3, 2023, from https://www.lazard.com/research-insights/levelized-cost-of-energyplus/
32. *Hydrogen production cost—An overview | sciencedirect topics*. (n.d.). Retrieved October 3, 2023, from https://www.sciencedirect.com/topics/engineering/hydrogen-production-cost
33. Nakano, J. (2022). *China's hydrogen industrial strategy*. https://www.csis.org/analysis/chinas-hydrogen-industrial-strategy
34. *What is hydrogen storage and how does it work?* (n.d.). Retrieved October 3, 2023, from https://www.twi-global.com/technical-knowledge/faqs/what-is-hydrogen-storage.aspx