Photo by Joshua Bauer, NREL 61789

Green Hydrogen: A Briefing for Land Managers

This briefing for land managers provides insight regarding the resources necessary for green hydrogen production and related activities on federal and state lands.

Hydrogen is a versatile energy carrier and chemical feedstock. Hydrogen can be extracted from diverse domestic resources such as water, biomass, and fossil fuels. Once produced, it can be stored, transported, and reacted to generate energy or produce higher-value chemicals and fuels.

National and state objectives toward decarbonization are including hydrogen produced from renewable electricity such as solar, wind, hydro, and geothermal—often referred to as "green hydrogen." Developers are identifying suitable locations that will support collocated renewable electricity and hydrogen production.

Hydrogen Properties

Hydrogen is abundant but is rarely found in its pure form. In the molecular form, it is odorless, colorless, tasteless, nontoxic, and highly flammable (at concentrations from 4% to 74% in air). As shown in Table 1, hydrogen has the highest energy content by weight of known fuels and low energy content by volume. However, because it must be dissociated from the compounds it is found in, hydrogen is not a primary source of energy but rather an energy carrier, like electricity.

Hydrogen Production

Commercial hydrogen is always derived from hydrogen-containing molecules such as water (H_2O) or natural gas (CH_4), and that production requires energy from heat, light, or electricity. Approximately 95% of domestic merchant hydrogen is produced from natural gas via steam methane reformation, a thermocatalytic process that also produces carbon dioxide (McQueen et al. 2020). This hydrogen is often

Table 1. Hydrogen Comparison to Common Fuels (U.S. Department of Energy Alternative Fuels Data Center)

	Hydrogen	Natural Gas	Gasoline	Diesel
Physical state	Compressed gas	Compressed gas	Liquid	Liquid
Energy per pound (Btu)	52,200	20,300	18,700	18,400
Energy per gallon (Btu)	Gas: 6,500 (3000 psi)	Gas: 35,500 (3000 psi)	120,400	138,500
Boiling temperature (°F)[1]	-423	-259	80-437	356-644
Freezing point (°F)	-435	-296	-40	-35

[1] Gasoline and diesel have wide boiling temperature ranges due to the variety of constituents in the fuel blend.

referred to by industry as gray hydrogen if the carbon dioxide is released to the atmosphere. It is labeled blue hydrogen if the byproduct carbon dioxide is captured and sequestered.

Hydrogen can be produced by splitting water via electrolysis, an electrochemical process. That process also produces oxygen from the water. Electrolysis is less efficient and more expensive than steam methane reformation (McQueen et al. 2020). Electricity from any type of power plant can be used for water electrolysis, and the resulting hydrogen is often given a name corresponding to the power supply. For example, green hydrogen is produced using renewable energy, and pink hydrogen is produced using nuclear energy. It should be noted that the U.S. Department of Energy is moving away from this "color" framework toward a framework that focuses more on the greenhouse gas emissions of various production methods.

The three prominent water-splitting electrolyzer technologies are polymer electrolyte membrane (PEM), alkaline, and solid oxide. In addition to technical and commercial maturity, these approaches have differing reaction pathways and process structures. PEM and alkaline electrolyzers operate at temperatures below the boiling point of water, while the solid oxide electrolyzer technology operates above 1,300ºF (McQueen et al. 2020).

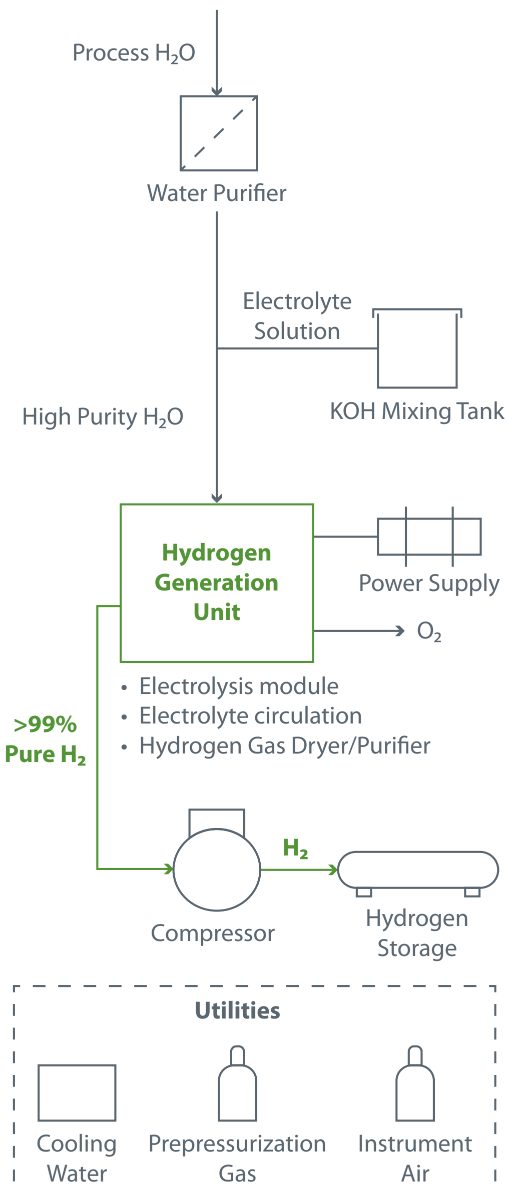

Figure 1. Process flow diagram for alkaline water electrolysis

Alkaline electrolysis is the least expensive, most mature commercial industrial-scale water electrolysis technology. A simple process flow diagram for alkaline electrolysis is provided in Figure 1 (Ivy 2004).

Process water must be high purity prior to blending the electrolyte solution (approximately 30% potassium hydroxide, KOH). Power supply delivered as alternating current is rectified to direct current and applied to the cathode to generate hydrogen gas. Hydroxide ions in the electrolyte migrate selectively through a diaphragm to the anode where oxygen gas is produced. The process requires cooling water for large-scale operations. Hydrogen gas is typically dried and purified to greater than 99.9%, then compressed and stored depending on the application. Oxygen can also be captured, dried, and compressed if there is a market (Ivy 2004).

Hydrogen Storage and Transport

Hydrogen is commonly stored under pressure in bulk as a gas or a liquid in tanks.

Liquid hydrogen can be stored as a cryogenic liquid (below -423ºF), but the liquefaction process is expensive and consumes 35% of the energy content of the hydrogen (McQueen et al. 2020). Further, liquefied hydrogen storage tanks must be heavily insulated, and, over time, the hydrogen is subject to boil off and venting. For liquid hydrogen, standard tank sizes range from 1,500 gallons to 25,000 gallons with size selection based on the application. Cylindrical tanks are commonly placed in a horizontal position, like a propane bullet tank, but vertical cylindrical and spherical tanks are also used (Air Products and Chemicals, Inc. 2013).

Stored as a gas, even under high pressure, the volumetric energy density of hydrogen is low, demanding substantial storage tank capacity. A tube trailer with multiple tubes can hold up to 300 kg per trailer and pressures can exceed 7,000 psi. Large-scale, long-term hydrogen storage can be accomplished in salt caverns and depleted natural gas reservoirs.

Photo by Joe DelNero, NREL 68238

Currently, most hydrogen is consumed at or near the location where it is produced, but hydrogen can be delivered regionally at scale using liquid or gaseous tube trailers, cylinders, and pipelines. Gaseous tube trailers are used for smaller quantities (less than 25 kg per day) (McQueen et al. 2020).

Hydrogen pipelines are common where long-term demand is high. The United States has more than 1,600 miles of dedicated hydrogen pipelines, mostly concentrated around the Gulf Coast petroleum refineries (McQueen et al. 2020). There, hydrogen is used to crack and desulfurize crude oil and to produce ammonia and methanol. A recent study by the California Public Utilities Commission found that a hydrogen blend of up to 5% in natural gas is generally safe. Blending more than 5% results in a greater chance of pipeline leaks and embrittlement of steel pipelines (Miroslav et al. 2022).

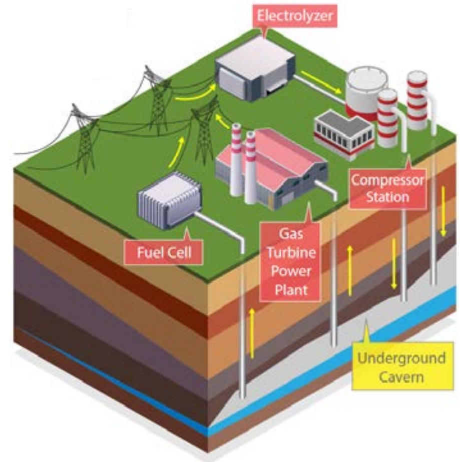

Figure 2. Hydrogen Storage System. *Illusration by Alfred Hicks, NREL 63328*

Green Hydrogen Facility Requirements

On June 3, 2022, Advanced Clean Energy Storage (ACES) Delta closed financing with the U.S. Department of Energy's Loan Programs Office and will be the world's largest green hydrogen production, storage, and delivery hub based on alkaline electrolyzer technology (Stribley 2022).

As the most mature technology, alkaline water electrolysis is reasonably representative of resource requirements for green hydrogen production. Energy, water, and land demands for the ACES Delta 100,000-kg/day green hydrogen plant (Phase 1) are summarized in Table 2. Additional detail is provided in the addendum.

The ACES Delta project suggests on-site provision of solar photovoltaic (PV) and wind generation as well as imported energy over high voltage lines. No information detailing energy provision for the project was provided in publicly available documentation. Project energy requirements, particularly for both Phase 1 and Phase 2, will be substantial and may be provided through a mix of on-site and local power generation and regional grid supply through virtual power purchase agreement or the purchase of renewable energy certificates to accommodate non-renewable energy supply from the grid. It also takes advantage of geological salt caverns present at the site for hydrogen storage. A solar

Table 2. Summary of ASES Delta Hydrogen Facility (Stribley 2022)[2]

Item	Value	Description
ENERGY		
Power	50–55 kWh/kg H_2	Includes parasitic loads
	220 MW	
Electricity	5,280 MWh/day	Full load 24 hours
	1.93 million MWh/yr	8,760 hours/yr
WATER		
Reaction water	9 kg (2.4 gal) H_2O/kg H_2	Stoichiometric for electrolysis
Demineralized process water	11.3 kg (2.9 gal) H_2O/kg H_2	200 gpm demineralized
Demineralization reject water	5.6 kg (1.4 gal) H_2O/kg H_2	100 gpm reject water
Total raw water for all plant uses	26.5 kg (6.9 gal) H_2O/kg H_2	468 gpm (755 acre-feet)
LAND		
Process and ancillary equipment	96 acres	Phase 2 ancillary space included
Wastewater pond	16 acres	Lined evaporation pond
Utility corridors	80 acres	100 to 300 ft wide
Access roads	45 acres	50 ft wide

[2] Certain information has been converted to reflect alternative units using standard conversion methods and recognized hydrogen production variables.

PV project capable of producing 100% of the ACES Delta plant's electric needs would have a nameplate capacity of approximately 800 MWac and would require approximately 4,000 acres.[3] This determination does not incorporate elements such as time of day, inclement weather, seasons, and other factors that limit reliance on variable renewable energy generation.

Hydrogen Shot

In June 2021, the U.S. Department of Energy launched Hydrogen Shot with the goal of reducing the cost of low-carbon hydrogen by 80%, from approximately $5 per kg to $1 per 1 kg in one decade (DOE).

Achieving this goal is expected to open the hydrogen market for use in steel manufacturing, green ammonia, biomass conversion, synthetic hydrocarbons, energy storage, and heavy-duty trucks. Currently, the cost of green hydrogen is five times the cost of gray hydrogen.

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Addendum

Additional mass and energy balance detail based on the world's largest manufacturer of alkaline electrolyzer systems is available in the referenced NREL report (Ivy 2004). In 2020, the International Renewable Energy Agency (IRENA) published a study on cost reduction opportunities for green hydrogen, including useful information related to alkaline electrolyzer facilities (IRENA 2020). These sources supplement the information provided on the ACES Delta green hydrogen project.

Energy

Energy required for a hydrogen production capacity of 1,000 kg/day is approximately 53.5 kWh/kg, and system power required is estimated at 2.3 MW (Ivy 2004). Parasitic load is 5% to 10%, with hydrogen produced as a lower-pressure gas (i.e., not high compression or liquefaction). Annual operating capacity should exceed 90% of nameplate, allowing for forced and unforced outages.

ACES Delta will convert 220 MW of renewable energy via alkaline electrolyzers into 100,000 kg per day of hydrogen in Phase 1, and Phase 2 will add 330 MW of electrolyzers. Full capacity will be 550 MW and 250,000 kg per day of hydrogen fuel. For comparison, the world's largest PEM project is the Becancour facility in Canada, a 20-MW electrolyzer producing up to 8,200 kg per day (58.5 kWh/kg).

The estimated nameplate solar PV capacity is based on a simple PVWatts analysis for the ACES Delta project location. First-year production for a nominal 1-MWac solar PV project is 2,900 MWh. After rectification and allowing for degradation, a 220-MW electrolyzer project would require the equivalent of an 800-MWac solar PV project. However, to meet project demand during the night, winter, inclement weather, and other times, a larger capacity and a significant amount of energy storage or backup power would be necessary for any on-site system not procuring energy from the grid.

Until broader demand for renewable energy outstrips supply, resulting in a resource-constrained market, a grid-connected green hydrogen project will have more energy supply options through virtual power purchase agreement(s) or renewable

[3] Simplified analysis for Delta, Utah, using PVWatts® assuming one-axis tracking, premium modules, 1.3 inverter loading ratio, 98% inverter efficiency, and default system losses. First-year production estimated at 2,500 kWh/kWac. Acreage estimate based on the lower end of the typical range of 5 to 7 acres per MW.

energy certificates. That said, a green hydrogen project will still require the input of variable renewable energy generation, whether on-site or otherwise.

Water

The ACES Delta project will require 755 acre-feet of groundwater annually or approximately 468 gpm for Phase 1. Water is required for the process and for the cooling water system. Process water is demineralized using a combination reverse osmosis/ion exchange process, with 200 gpm of demineralized water flowing to the electrolyzer and 100 gpm rejected to the wastewater pond for evaporation. Brackish water would require more untreated water supply and result in more reject water to the wastewater pond, but quantities are highly dependent on brackish water quality.

Additional water is used for drinking water, sanitation, and fire safety and suppression. ACES Delta estimates the peak volume of cooling water discharge is 65 gpm. At 468 gpm total water supply and 100,000 kg per day, ACES Delta has estimated consumption of 26.5 kg of water per 1 kg hydrogen. Cooling water requirements could be reduced by application of hybrid or dry-cooling technology, but process efficiency will be lost.

IRENA's report recognizes that 9 kg of water is required for 1 kg of hydrogen on a pure, stoichiometric basis, but the process of demineralization results in a typical water consumption range between 18 kg and 24 kg of water per 1 kg hydrogen. The higher end of this range is consistent with the ACES Delta project assumptions.

Utility Easements

ACES Delta includes several utility and access corridors for electrical, water, access roads, and hydrogen distribution. This network of easements includes 50-, 100-, and 300-foot-wide corridors. Additional detail is described under the land requirements.

Land

Land requirements for ACES Delta is nearly 750 acres, but that includes almost 400 acres for brine evaporation ponds to support solution mining for the underground storage caverns. Given the unique location of the ACES Delta site's salt caverns, these brine ponds will likely not be necessary at other locations. Rather, hydrogen storage is likely to occur in depleted underground oil and gas reservoirs or aboveground tank storage.

Of the remaining acreage for the ACES Delta project, 96 acres is for the Phase 1 project and includes ancillary equipment space for both Phase 1 and Phase 2. The Phase 2 surface requirement is 33 acres, primarily for the electrolyzer plant. A wastewater pond for the process will require 16 acres. This pond should accommodate both the demineralizer water treatment for the process, cooling tower makeup water treatment and blowdown, and water treatment for potable, sanitary, and fire response purposes.

Linear corridors will include a 46-acre utility corridor (100 ft wide), 45 acres of access roads, and over 36 acres for the high-voltage electrical corridor (300 ft wide). Some utilities may overlap in corridors.

As discussed, ACES Delta did not address the provision for solar PV on-site. Based on a PVWatts analysis showing a nominal capacity of 800 MWac, the land requirement for just the solar PV generating facility is estimated to be 4,000 acres. This would be equivalent to the current largest solar PV project in the United States, the Copper Mountain Solar Facility in Boulder City, Nevada.

Permitting

A large-scale hydrogen production facility requires numerous permits. ACES Delta has been in the planning and permitting stage for a few years, and by the time construction is finished and operations begin, about 5 years will have passed since the project was initially proposed. A complete list of permits is provided in the ACES Delta Environmental Assessment.

Employees

Approximately 18 to 20 full-time employees are estimated for the operation of ACES Delta Phase 1, staffed 24 hours per day and 7 days per week. Construction is expected to require 400 workers.

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