CAPTIVE-USE HYDROGEN FOR ADVANCED AIR MOBILITY

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ABSTRACT

Hydrogen is viewed as a viable energy source for aviation, but is often ruled out due to cost, public perception of safety, and underdeveloped infrastructure. Further, most current production methods rely on fossil fuels, thus negating the carbon-neutral potential of hydrogen. This paper shows that on-site hydrogen production and storage can be accomplished by integration and innovation of current technologies. Efforts are underway to accomplish this more efficiently and with smaller footprint.

EXECUTIVE SUMMARY

In 2018, traffic congestion cost the United States $305 billion in lost productivity.[1] Efforts to expand roadway capacity are costly and have only resulted in worsening congestion and increased greenhouse gas (GHG) emissions. Moreover, adding lanes requires miles of land that could be otherwise preserved. As the human population continues to grow exponentially, it becomes clear that additional road infrastructure is not a viable answer to traffic congestion. Seventy percent of the global population will live in urban areas by 2050. People in these locations will require different mobility solutions.[2]

> “NOW, TECHNOLOGY CAN ENABLE THE SAME ON-DEMAND EXPERIENCE IN AVIATION.”
>
> **-Dr. Jaiwon Shin**

Affordable on-demand air travel for all is becoming a real possibility as technology progresses at unprecedented rates. On July 24, 2018, former NASA associate administrator Dr. Jaiwon Shin participated in House Committee on Science, Space, and Technology "Urban Air Mobility - Are Flying Cars Ready for Take-Off." During the hearing, Dr. Shin stated that technologies are ready to support on-demand aviation just like other technologies have been delivered on-demand. [2] Rather than sit in traffic for hours, we could fly above in an automated air taxi, all for close to the price of an Uber Black.[3] Hundreds of startups and legacy companies are developing aircraft to do just that.

Emissions can be significantly reduced if these aircraft are electric. Constructing runways and roads will not be needed because air taxis will take off and land vertically. Retrofitted rooftops, parking garages, helipads, and new innovative structures are the only infrastructure needed, preserving thousands of acres of land.

> ‘IT IS CLEAR THAT HYDROGEN POWERED AIRCRAFT WILL LIKELY DOMINATE THE SKIES’

Most electric vehicles are battery powered. Batteries offer adequate specific energy, but impose payload, flight duration, and range limits. With a much higher energy density, hydrogen fuel cells, in combination with batteries, provide a compelling alternative.

Hydrogen fuel cell vehicles are forecasted to become cheaper than batteries and internal combustion engines by 2026.[4] Hydrogen can also be refueled quickly, has zero harmful emissions, and is the most abundant element in the universe. However, hydrogen does not come without its challenges. It is expensive to transport, difficult to store, and often made with methods using fossil fuels that emit more GHGs than the hydrogen negates. Technology exists to make hydrogen from all renewable resources. Furthermore, if captive hydrogen (hydrogen that is made on-site at the refueling station) is taken advantage of, inefficient transport can be eliminated. Incredible innovations in hydrogen storage are being made to advance the maturity of hydrogen aircraft.

Electric vertical takeoff and landing aircraft, commonly referred to as eVTOLs, will likely follow a trajectory like the automotive industry. The first eVTOLs will enter the market powered by a hybrid of jet fuel and batteries. As hydrogen technology advances, the engines can be exchanged for fuel cells. Hydrogen-powered eVTOL aircraft such as Skai and CityHawk are currently flight testing and working toward certification, so hydrogen infrastructure will be needed.

For hydrogen-powered aircraft to succeed, hydrogen must be stored and used safely. Historically, especially in the high-profile case of the Hindenburg disaster, hydrogen has procured an unfavorable public perception. However, the Hindenburg disaster was a result of poor design and planning. Today, the physical and chemical properties of hydrogen are better understood than in Hindenburg's day. The storage and transport of hydrogen has developed in both design and materials to minimize risk, making it a safe and low-risk option for transportation.

Hydrogen refueling stations are of grave importance for the success of hydrogen fuel-cell vehicles. California is the only state in the US that is earnestly pursuing hydrogen infrastructure. Even with California's efforts, much development is still needed for fuel-cell vehicle proliferation. Japan, Europe, China, and the United States were evaluated for this paper. As of this writing, **the United States has the fewest, with only 40 hydrogen refueling stations**. Japan is leading the world in hydrogen infrastructure, having 160 refueling stations. Europe comes in second with 152 refueling stations, most of which are in Germany. China comes in third, having 100 refueling stations The United States plans on having 1000 stations by 2030, which is comparable to the goals of China and Japan, but far behind Europe, who plans on having 3700.

> 'THE UNITED STATES WILL NEED TO INCREASE ITS EFFORTS TO BE COMPETIVE IN THE EMERGING FUEL CELL MARKET'

INTRODUCTION

At the time of this writing, most eVTOL designers rely on some form of lithium battery packs to satisfy their power demands. While lithium-ion battery technology has seen significant energy density improvements over the past decades, proliferation of battery powered eVTOLs has multiple challenges. Uber Elevate desires energy densities of 400 Wh/kg with charge times of 10 minutes.[5] Roland Berger estimates an even higher energy density requirement of 500 Wh/kg for urban air taxis. Even at the high-end, energy density is still poor in comparison to jet fuel, which is over 10 kWh/kg.[6]

Attaining attractive trip costs is dependent on throughput, which correlates with charge time. Currently, it takes between 90 minutes and two hours to charge batteries of this magnitude. This constraint will likely create a bottleneck at the charging station and reduce throughput capacity. Battery swapping is being considered by many developers to overcome this constraint, though stations could eventually run out of batteries due to extended charge time of depleted batteries relative to a charged battery's install time. Fleet manufacturing costs are also affected by turnover delay. It is speculated that fleet size could triple because two vehicles will be charging for each one in operation. Consequently, two thirds of the fleet would be grounded.

Parameter	**Air Transportation Requirements**	**Current Value (Li)**	**Prototyping, Demoing 2020**	**Real Business, Ride Sharing, from 2023**
Energy Density	500Wh/kg	180Wh/kg	**OK**	**NOT OK**
Specific Power	1500W/kg	1500W/kg	**OK**	**OK**
Charging Time	10 min	2 hours	**OK**	**NOT OK**

Table 1: Li-ion Technology[6]

It is also critical to consider the process of procuring resources necessary for producing electric powertrains. Large battery packs needed for eVTOLs require a vast amount of lithium. Lithium is a nonrenewable, finite resource. Lithium is recyclable, but it is not practical to use nonrenewable materials when attempting to replace fossil fuels. Conversely, hydrogen is the most abundant element in the universe. It also has more energy density than lithium-ion batteries[7], may require smaller fleets than lithium-ion powered aircraft, can be refueled quickly, and has zero harmful emissions. Hydrogen offers a promising renewable, affordable, and environmentally friendly option to electrify the skies when produced with renewable energy sources.

A disadvantage of hydrogen is that it has poor specific power, meaning that it is not ideal for the quick delivery of power required during hover. On the other hand, batteries have enough specific power to perform air taxi operations (see Table 1). The ideal configuration for eVTOL powerplants is a hybrid battery/fuel cell combination that uses batteries for takeoff and landing and fuel cells for cruise. This synergistic approach offers increased range, reduced lithium or hydrogen requirements, and overall superior performance than either powerplant by itself.[7]

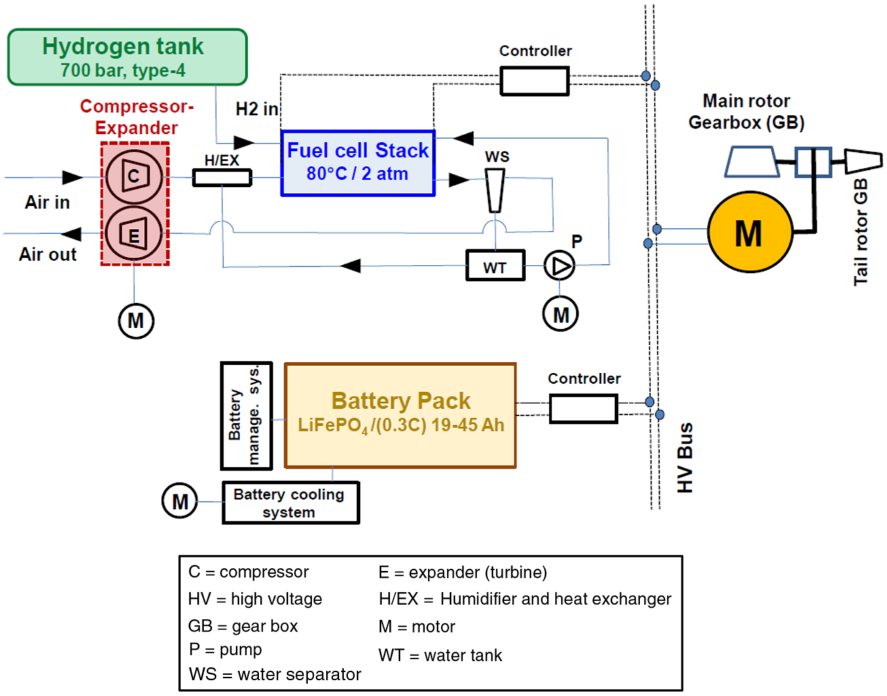


Figure 1: Hybrid Battery Fuel Cell Configuration [8]

Infrastructure for battery/fuel cell designs will require both recharging of batteries and hydrogen refueling. Hydrogen is expensive and difficult to transport. Therefore, it is believed that producing hydrogen at the refueling station is the most viable way to utilize hydrogen as a fuel. There are several renewable sources available today to produce hydrogen. Potential options include solar, wind, water, geothermal, and biohydrogen. The energy to produce the hydrogen could come from an established renewable energy supplier or be harnessed at the refueling station. This paper analyzes safety and public perception of hydrogen. Also evaluated is existing infrastructure, and renewable energy sources implemented at the refueling station for viability of microgrid applications that enable on-site production of hydrogen fuel.

SAFETY OF HYDROGEN FUEL

PROPERTIES OF GASEOUS HYDROGEN

In its pure molecular form, hydrogen provides a fuel that is both energy dense and clean. Fuel cells harness this energy by controlled reactions combining pure H_2 and O_2 into H_2O molecules, using the electron exchange in the reaction to drive the current that powers an electric motor. Gaseous hydrogen is odorless and nontoxic, and the only byproduct of this reaction is water. Hydrogen can be stored as a gas, liquid, hydride, or slush. This paper focuses on gaseous hydrogen as it is perceived to be the most dangerous.

Hydrogen has a diminutive molecular weight, which provides unique challenges to confinement in storage vessels. This tiny molecule can easily pass through tiny cracks or seals. The greatest risk in the event of a hydrogen leak is accumulation in a confined area, which can result in concentrations high enough for combustion. These potential collection spaces are routinely monitored and vented with positive air pressure, disbursing any released hydrogen down the air concentration gradient to eventually disburse harmlessly into the atmosphere.[8]

Hydrogen gas is highly flammable and potentially explosive in high concentrations, though nearly all ignitions result in deflagration (flash fire) rather than detonation. Deflagration reactions can occur with concentrations as low as 4%, while detonation requires a concentration minimum of 18.3%.[9] A study by the National Hydrogen Association in 1991 compares hydrogen to hydrocarbon fuels like methane and propane. Hydrogen was found to form a burnable mixture faster than the other fuels and has the lowest spark ignition energy of only 0.02 milliJoules. This amount of energy may occur in a small static discharge, resulting in a very low ignition threshold. However, when released into vented spaces hydrogen dissipated so quickly that virtually no combustible mixture was measurable. In similar tests, propane formed a large combustible mixture and methane yielded a small but significant mixture.[8]

The key consideration in the safety of hydrogen is the space in which spark exposure may occur. In confined spaces where concentration may be increased, detonation becomes a concern. The primary hazards in this scenario are shrapnel injury and displacement of oxygen. Hydrogen combustion does not produce toxic gases, and nearly always results in a flash fire rather than detonation. Hydrogen gas itself is nontoxic, though in extremely high concentrations may displace oxygen making asphyxiation a concern.[8]

When exposed to atmospheric air, hydrogen's miniscule molecular weight facilitates extremely rapid diffusion that minimizes ignition potential. In the event of a leak producing a jet stream of hydrogen, the area of release contains such a high concentration of hydrogen that no oxygen is available to facilitate combustion. The cloud perimeter where hydrogen mixes with oxygen, however, is susceptible to ignition and deflagration that will persist until all fuel is exhausted. Concentrations capable of enabling a detonation explosion are unlikely to occur.[10]

THE HINDENBURG DISASTER

The Hindenburg is the most well-known dirigible catastrophe but was preceded by numerous other airship disasters. World War I saw the utilization of hydrogen-filled airships by the German military for scouting, reconnaissance, and bombing raids targeting cities in the United Kingdom. At the time, rigid-structured airships avoided ignition by keeping hydrogen in isolated chambers away from oxygen. Strict guidelines were employed to avoid ignition. Weather was closely monitored and venting of hydrogen was restricted during thunderstorms. These measures enabled the airships to survive many lightning strikes.[10]

After the war, there was much interest in dirigibles for transportation. In 1921, the United States purchased an R-38 zeppelin from the United Kingdom and renamed it to Zeppelin Rigid-2, or ZR-2. The ship was preparing for a transatlantic flight from Hull, England to be delivered to the United States. En route to port for refueling, the girders buckled in the middle causing a split across the bottom of the ship. The bow and stern sections rose as the split increased, and the ship plummeted into the nearby Humber river. The forward section ignited during the descent and spread to the aft section, causing an explosion affecting a 2-mile radius.[12]

By 1937, technology advances enabled video recording. This is perhaps why the Hindenburg incident is so widely known, despite causing fewer fatalities than previous dirigible accidents. Another factor is escalating political tensions between the United States and the Nazi-controlled German government. The swastika emblem prominently emblazoned upon Hindenburg's fins was forever captured in video footage, along with the now-famous proclamation, "oh, the humanity!" This emotional plea was uttered by Chicago reporter Herb Morrison while filming the airship docking procedure near Lakehurst, New Jersey on May 6, 1937.[11]

Prior to that fateful day, the Hindenburg had made thirty-four successful transatlantic voyages between Lakehurst and Rio de Janiero, Brazil. On May 6, the airship was scheduled to arrive in Lakehurst early in the morning but was delayed by weather during the crossing. To avoid additional lost time, the Hindenburg underwent an unconventionally sharp turn maneuver into the wind. Hemp mooring ropes were dropped from each side, and a light rain saturated the material. The port side rope was retrieved first and attached to its winch.[12]

On approach, the Hindenburg's nose was observed to be tilting upwards, and 6 crew members were ordered from the aft to the bow in attempt to ballast the ship. Around this time, ground crew members noticed an area of flapping skin material in the top aft section on the port side. These observations immediately preceded the flash fire that started in the flapping skin area. The fire spread quickly from stern to bow as the loss of hydrogen caused the stern to plummet towards the ground. Thirty-two seconds later, the Hindenburg was reduced to a smoldering aluminum skeleton resting on the ground. Thirty-six people lost their lives as a result.[12]

An exhaustive investigation soon began amid public outcry and suspicion of sabotage. US and German teams, of which Dr. Hugo Eckener, the German designer of the Hindenburg and operations expert, found sabotage to be unlikely. The destruction of evidence in the fire negated definitive understanding of the cause. The most probable scenario, as put forth by the research teams, was a static discharge event correlated with a leaking hydrogen cell.[12]

The aggressive turn maneuver is likely to have severed a support cable, which could have recoiled and damaged the membrane of the hydrogen cell. This would explain the fluttering phenomenon that was witnessed. The Hindenburg would have acquired a voltage potential gradient relative to the ground while flying through Atlantic storms. The hemp mooring rope is a poor conductor, but water saturation would have enabled grounding and static discharge once attached. This would have resulted in a charge with more than enough energy ignition potential to meet the combustion threshold.[11]

The Hindenburg disaster was an unfortunate and unnecessary tragedy. It has affected public perception of the safety of hydrogen gas and toppled the dirigible industry. That said, modern applications of hydrogen differ in many ways from the older technology. The hydrogen cells within the Hindenburg were constructed from cotton fabric. A rubberized layer was applied to the fabric, then another layer of cotton fabric. The sixteen hydrogen cells were contained within a protective outer skin that was coated with aluminum powder for weather protection. Red paint was applied to the inner layer to protect from ultraviolet radiation.[13]

Today, hydrogen is safely stored in non-combustible high-pressure steel alloy or composite systems. These systems are redundantly monitored for leakage and possess many emergency shut-off valves to neutralize propagation of fire. Temperature dysregulation causes relief valves to discharge stored hydrogen upwards into the atmosphere where it harmlessly dissipates into atmospheric gases.[14] Hydrogen properties are better understood, and safety guidelines have been made available by OSHA, NASA, and the US Department of Energy, among several other organizations. The chemical and physical properties of hydrogen, when understood and respected, enable safe storage and usage of this energy-dense and relatively affordable gas.

HYDROGEN INFRUSTRUCTURE

Japan, Europe, China, and the United States were considered for this paper. Currently, Japan is leading the world in hydrogen having 160 refueling stations and plans to have 900 by 2030. Europe comes in second with 152 refueling stations, most of which are in Germany. Europe plans to dominate the industry with goals of having 3700 stations by 2030. China comes in third, having 100 refueling stations and plans to have 1000 by 2030. The United States currently has 40 stations, coming in last of the four locations. The United States plans on having 1000 stations by 2030, which is comparable to China and Japan but far behind Europe.

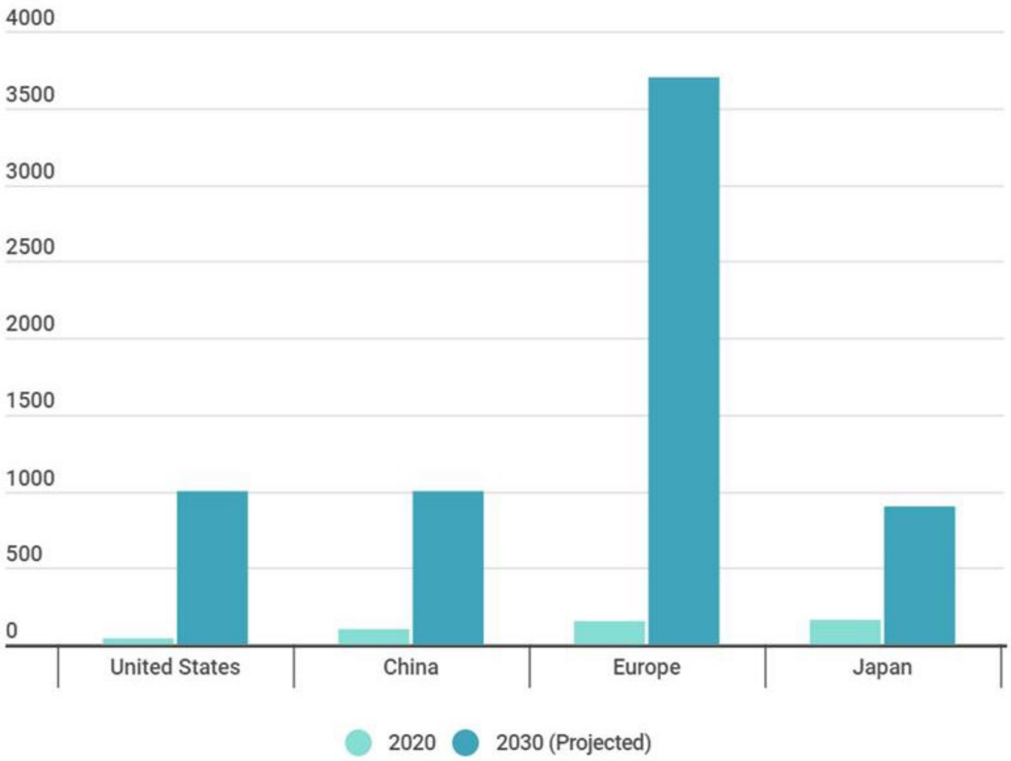


Figure 2: Hydrogen Refueling Stations

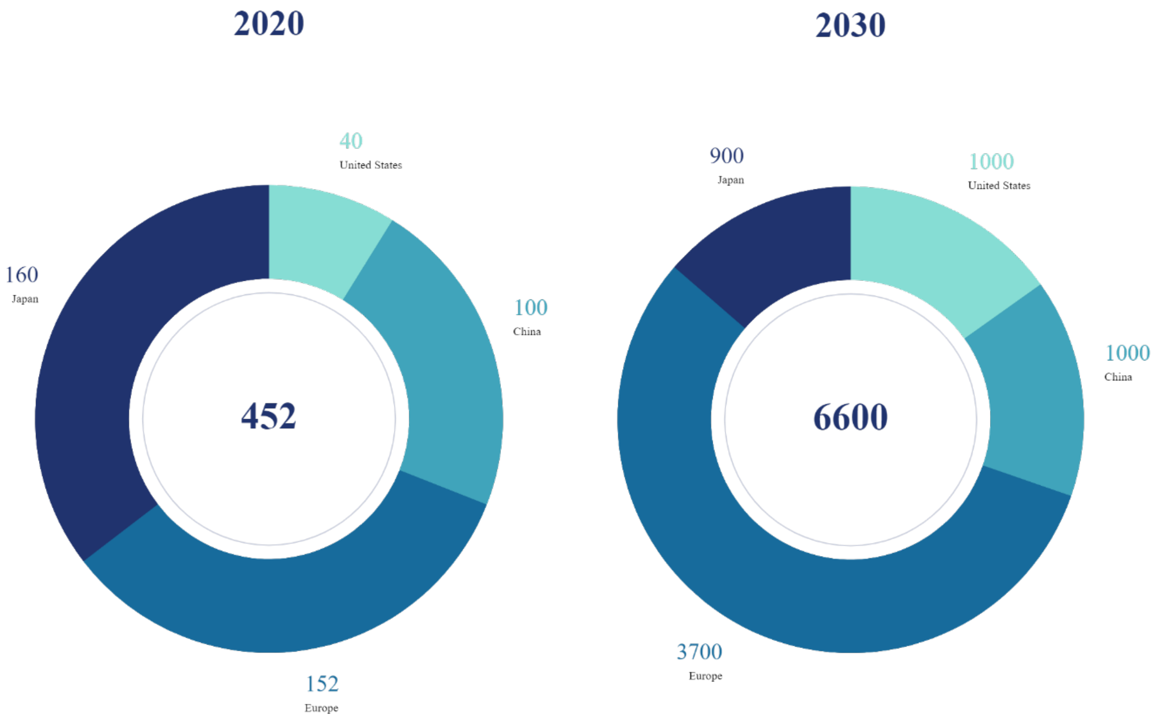


Figure 3: Hydrogen Infrastructure Comparison

JAPAN

Japan is the global leader in hydrogen infrastructure. On December 26, 2017, Japan released its Basic Hydrogen Strategy which declared Japan's commitment to be the world's first "Hydrogen Society." Currently, Japan has 160 refueling stations and plans to build 80 more by 2021. Around $1.3 billion has been invested in hydrogen research and development in support of renewable hydrogen production, infrastructure, and scaling up hydrogen usage.[21]

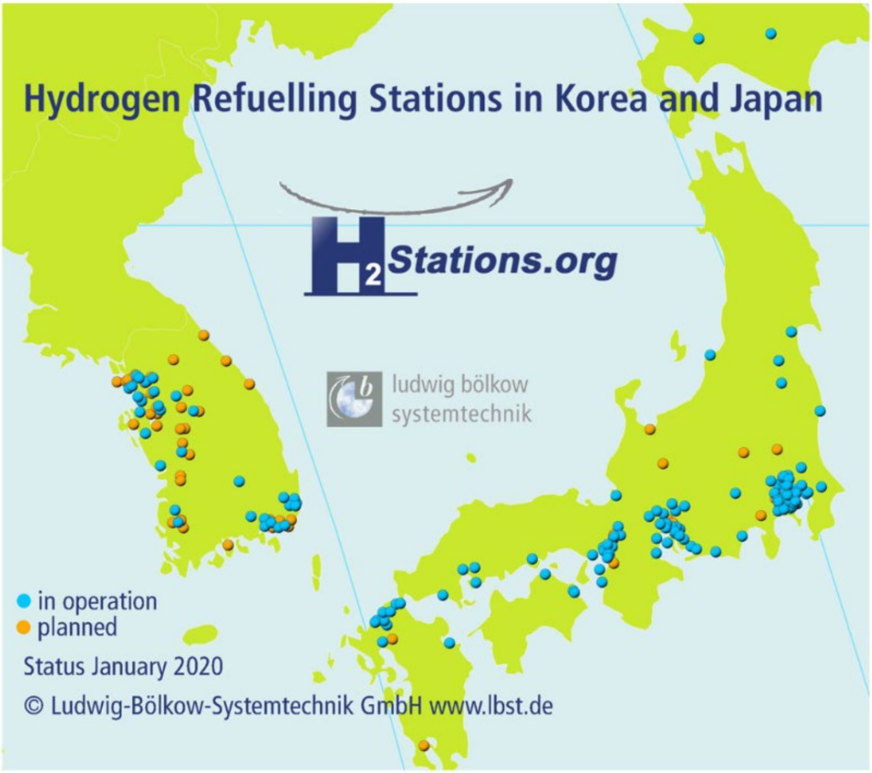


Figure 4: Hydrogen Infrastructure in Japan[22]

EUROPE

Europe is just behind Japan in leading the world with hydrogen refueling stations. Germany has over 60 refueling stations and plans to build 100 more by 2021. Before the COVID-19 outbreak, Germany was averaging about one new station built every two weeks. Europe's 2019 hydrogen roadmap stated that the European Union (EU) will not meet its goal of less than 770 megatons of CO_2 by 2050 unless it uses hydrogen at large scale. Furthermore, hydrogen and hydrogen-based synthetic fuels are the only known scalable options for decarbonization in aviation.[19]

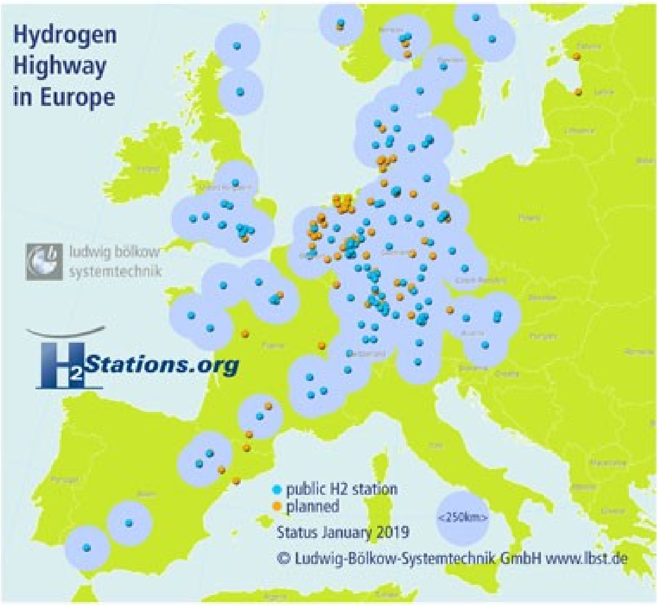


Figure 5: Hydrogen Infrastructure in Europe[20]

CHINA

China is one of the largest users and producers of hydrogen. In 2015, China released its 10-year plan for upgrading its manufacturing new energy vehicles (NEV) and the infrastructure to support them. Although there are no nation-wide subsidies on hydrogen refueling stations, there are city-level subsidies. Foshan allows 8 million RMB for each newly constructed hydrogen refueling station.[17] China currently has 100 hydrogen refueling stations and plans to have 1000 by 2030.

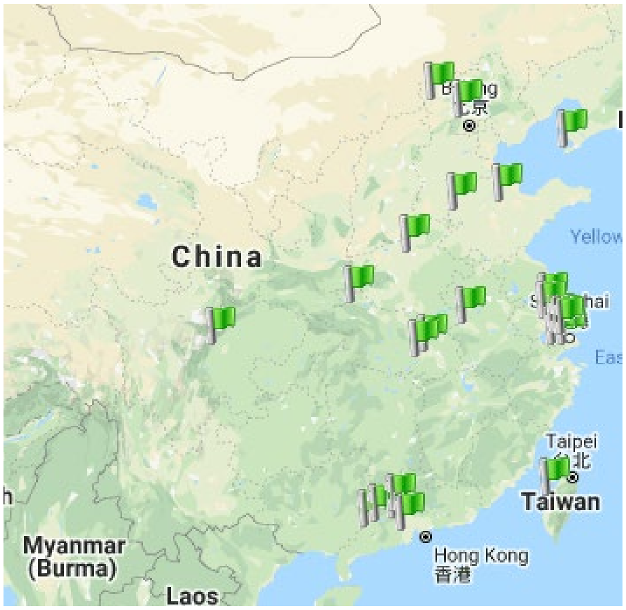


Figure 6: Hydrogen Refueling Stations in China[18]

UNITED STATES

There are about 40 hydrogen refueling stations in the United States, mostly in California. California has seen more advancements in hydrogen than any other state because of its government and public support for renewable energy. There are around 7,000 light-duty fuel-cell electric vehicles (FCEV) currently operating in California. The state has set a goal of 1,000 hydrogen refueling stations and 1,000,000 FCEVs by 2030.[15] The Department of Energy (DoE) announced on June 23, 2020, that it plans to invest up to $100 million on hydrogen production and fuel cell applications. This includes heavy-duty trucks, which have similar power requirements as eVTOLs, so the infrastructure to support ground vehicles could be used by air taxis, providing cross-industry growth.

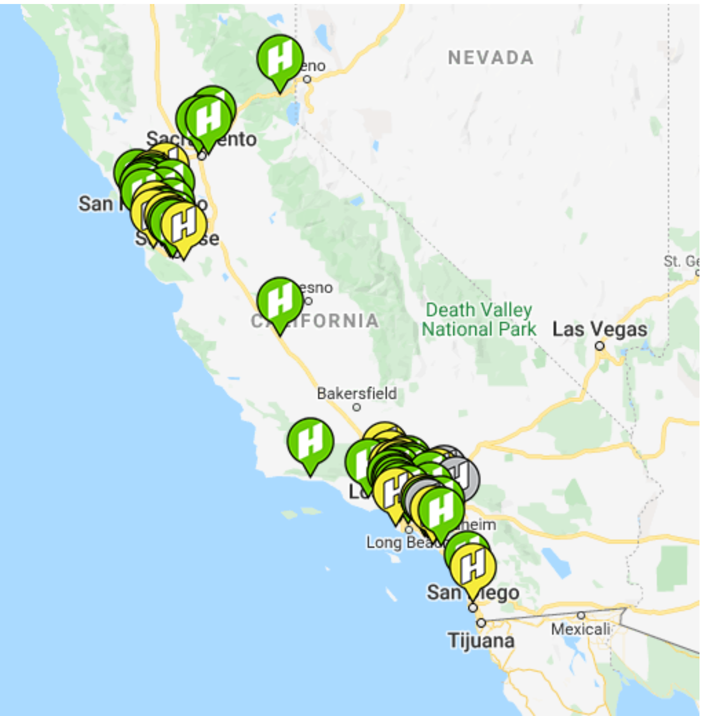


Figure 7: California Hydrogen Refueling Stations[16]

ELECTROLYSIS OF WATER

Electrolyzer technology operates similarly to hydrogen fuel cells, using electricity and water to produce hydrogen fuel. If used in conjunction with a renewable and clean energy source, products consist of hydrogen, which is collected, and oxygen, which is environmentally agnostic. Electrolyzers consist of a cathode and anode separated by an electrolyte. Different electrolyte materials can be used, including polymer electrolyte membrane (PEM), alkaline electrolyte, or solid oxide ceramics.[23] The earliest viable models of electrolyzers use liquid alkaline, and this remains the predominate method as of this writing.[24] Hydrogen is generated by transporting hydroxide ions (OH^-) through the alkaline electrolyte solution, typically sodium or potassium hydroxide, from cathode to anode, as seen in Figure 4.[25]

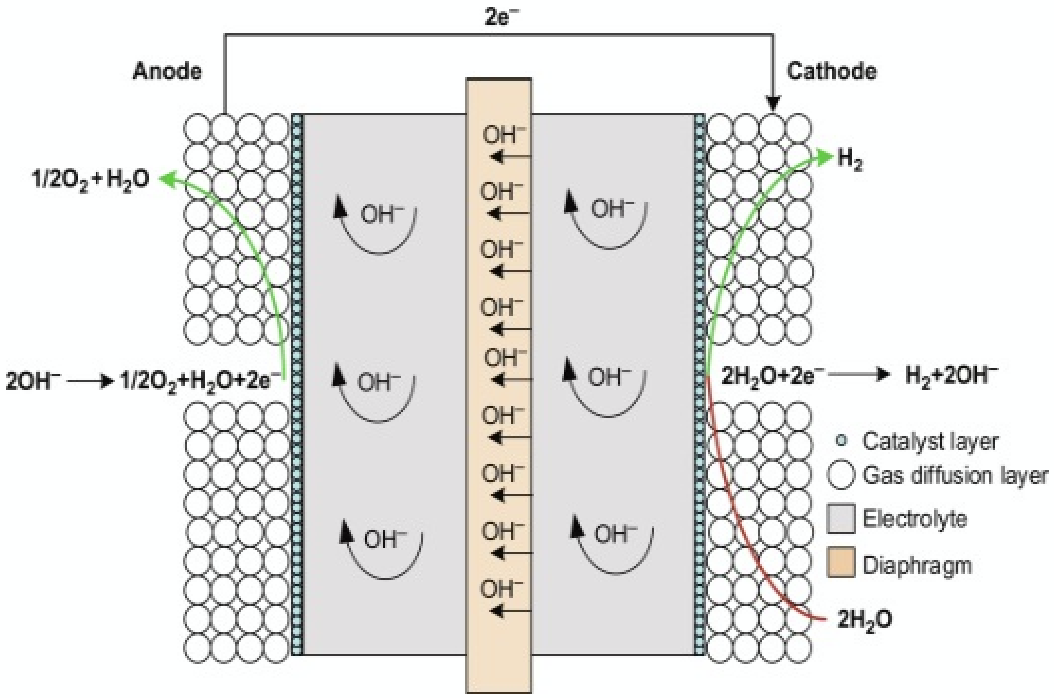
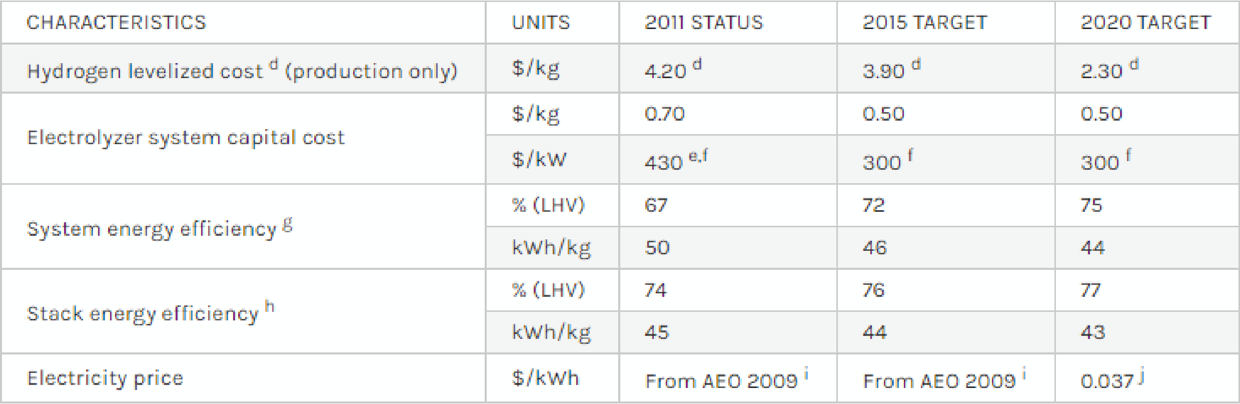


Figure 8: Alkaline Electrolyzer [24]

Alkaline electrolyte, being the earliest and most widely used method, is also the most studied. The US Department of Energy has published an analysis of this method including cost predictions and system efficiency (kWh/kg H_2), as seen in Table 3. System energy efficiency was considered as opposed to stack efficiency, as it includes operational electricity consumption for a more conservative and realistic result. Stack energy efficiency does not consider this constraint. It is therefore concluded that a theoretical input of 44 kWh is required per kg of H_2 produced on-site as of this writing.[25] This value will likely improve as technology is further innovated.



CHARACTERISTICS	UNITS	2011 STATUS	2015 TARGET	2020 TARGET
Hydrogen levelized cost [d] (production only)	$/kg	4.20 [d]	3.90 [d]	2.30 [d]
Electrolyzer system capital cost	$/kg	0.70	0.50	0.50
	$/kW	430 [e,f]	300 [f]	300 [f]
System energy efficiency [g]	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack energy efficiency [h]	% (LHV)	74	76	77
	kWh/kg	45	44	43
Electricity price	$/kWh	From AEO 2009 [i]	From AEO 2009 [i]	0.037 [j]

Table 2: Technical Targets for Distributed Water Electrolysis Hydrogen Production[26]

CONVERSION OF ENERGY INTO HYDROGEN

The following equations were derived to approximate and compare the efficiency of evaluated renewable energy sources, as applied to on-site hydrogen production. For comparison, these calculations provide the theoretical yield of hydrogen fuel per acre of land, per day. Technologies utilizing these sources will be discussed in their correlating sections.

To calculate solar electric hydrogen potential, *Eq (1)* was derived using the electrolyzer system efficiency of 44 kWh/kg H_2, as discussed in the previous section. California was selected as an ideal location in the United States because it receives an average of 5.82 peak sunlight hours per day[27] and has made significant progress in hydrogen infrastructure implementation.

Solar
(Electricity)

$$\frac{43{,}560\,ft^2}{1\,acre} \times \frac{module}{ft^2} \times \frac{kW}{module} \times \frac{kWh}{kW \times hr} \times \frac{5.82\,hr}{1\,day} \times \frac{1\,kg\,H_2}{44\,kWh} = \boldsymbol{kg\,H_2/acre\,/day} \qquad \text{Eq (1)}$$

Utilizing concentrated solar power does not necessarily require electricity as an intermediate, instead using heat to drive electrolysis in conjunction with a catalyst. Thus, equation 2 omits the electrolyzer conversion factor in consideration of this technology.

Solar
(Direct Thermal)

$$\frac{43{,}560\,ft^2}{1\,acre} \times \frac{module}{ft^2} \times \frac{kg\,H_2}{module} \times \frac{5.82\,hr}{24\,hr/1\,day} = \boldsymbol{kg\,H_2/acre\,/day} \qquad \text{Eq (2)}$$

For wind power, *Eq (1)* was modified to allow for 24-hour operation, as wind is not limited by sunlight. Other factors, such as average wind speed and efficiency, will be considered and discussed in the appropriate section.

Wind $$\frac{43{,}560\ ft^2}{1\ acre} \times \frac{turbine}{ft^2} \times \frac{kW}{turbine} \times \frac{kWh}{kW \times hr} \times \frac{24\ hr}{1\ day} \times \frac{1\ kg\ H_2}{44\ kWh} = \boldsymbol{kg\ H_2/acre\,/day}$$ Eq (3)

SOLAR

Sunlight is a globally available energy resource that is renewable, abundant, and free. It is typically collected in one of two ways: conversion to electricity via photovoltaic cells; or as heat, which can be used as is or converted to electricity. Solar arrays offer energy collection without air, water, or noise pollution. This technology has few if any moving parts, offering low operating costs and minimal maintenance. Constraints of this technology include cost and efficiency, as production is limited by peak daylight hours.

PHOTOVOLTAIC CELLS (PV)

PV cells are solid-state devices that collect sunlight and converts it into electricity. Individual cells are combined to create a module, using metal to direct the current. Typically made of silicon, this technology has no moving parts, so maintenance is minimal with a relatively long lifespan. The modularity of this technology allows it to be utilized as an isolated microgrid or connected to the common grid to contribute excess power. Modules can also be added to the array to increase overall output.[28] PV cells are commercially available in many different formats. The most viable commercially available PV technologies for on-site hydrogen production are reviewed in this section.

HIGH-EFFICIENCY FLAT PLATE MODULES

Many types of PV cells are available with varying degrees of efficiency. Monocrystalline silicon cells offer high efficiency, though production cost is higher due to the necessity of a single crystalline lattice. These cells are offered commercially with efficiencies up to approximately 20%, as compared to amorphous silicon thin-film cells which offer only 6-7% efficiency.[29]

Renewable Energy Corporation (REC) offers its Alpha Series modules boasting 21.7% efficiency. P_{max} ratings of these modules are available up to 380 W per 18.8 ft^2.[30] Using these values, *Eq (1)* provides a theoretical hydrogen production rate of 116 kg H_2 per acre per day. Utilization of single axis tracking systems can improve efficiency by 13%, while dual axis systems provide 25% more efficiency[31] for 131 kg and 145 kg per acre per day, respectively.

CYLINDRICAL MODULES

Cylindrical photovoltaic modules are designed in a hexagonal cylinder for 360° sunlight accessibility, maximizing peak daylight time without the necessity of tracking technology. Current designs utilize monocrystalline silicon cells for efficiency up to 21.8%. Modularity is incorporated into this design, so vertical expansion is possible to maximize surface area. Fluctuations in height via pole mounting and the number of peak hours affected by the 360°

design may also affect overall accessible surface area, so actual efficiency may exceed theoretical calculations.

OkSolar140, a cylindrical module produced and sold by OkSolar[31], has a P_{max} rating of 140 W per unit. Overall length for this model is 1,560 mm (61.4 in) and width at widest point is 228 mm (8.97 in) [See Figure 5]. For the purpose of this theoretical example, 4 ft^2 per unit was allotted to allow adequate spacing. Fluctuations in height via pole mounting may also affect overall accessible surface area, so actual efficiency may exceed theoretical calculations. Considering these values in *Eq (1)*, this technology is estimated to produce 202 kg H_2 per acre per day. Implementing vertical expansion could potentially double, or even triple, this number.

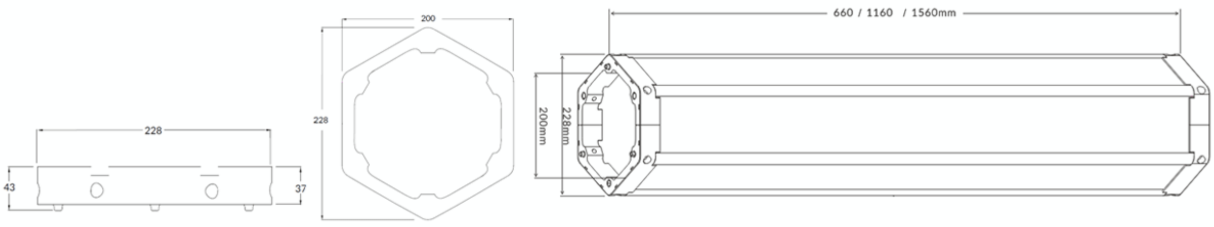


Figure 9: OkSolar140 Dimensions[32]

CONCENTRATING SOLAR POWER (CSP)

CSP technologies collect sunlight and use reflective surfaces to concentrate solar energy on a receiver located at the focal point, thereby converting it to heat. Heat is transferred via fluids passing through the receiver and thermal energy is stored in a reservoir, which can be used directly as heat or converted into electricity by a steam turbine generator.[33] Figure 6 demonstrates the four primary CSP configurations: solar power tower, parabolic trough, linear Fresnel reflector, and parabolic dish.[33]

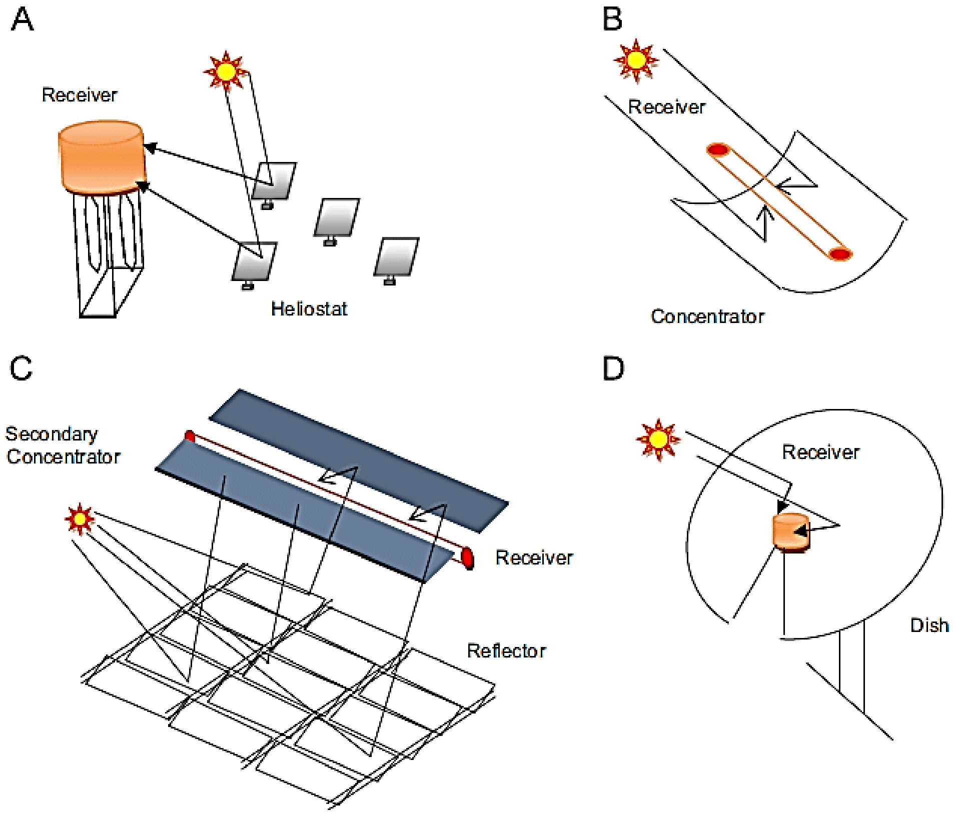
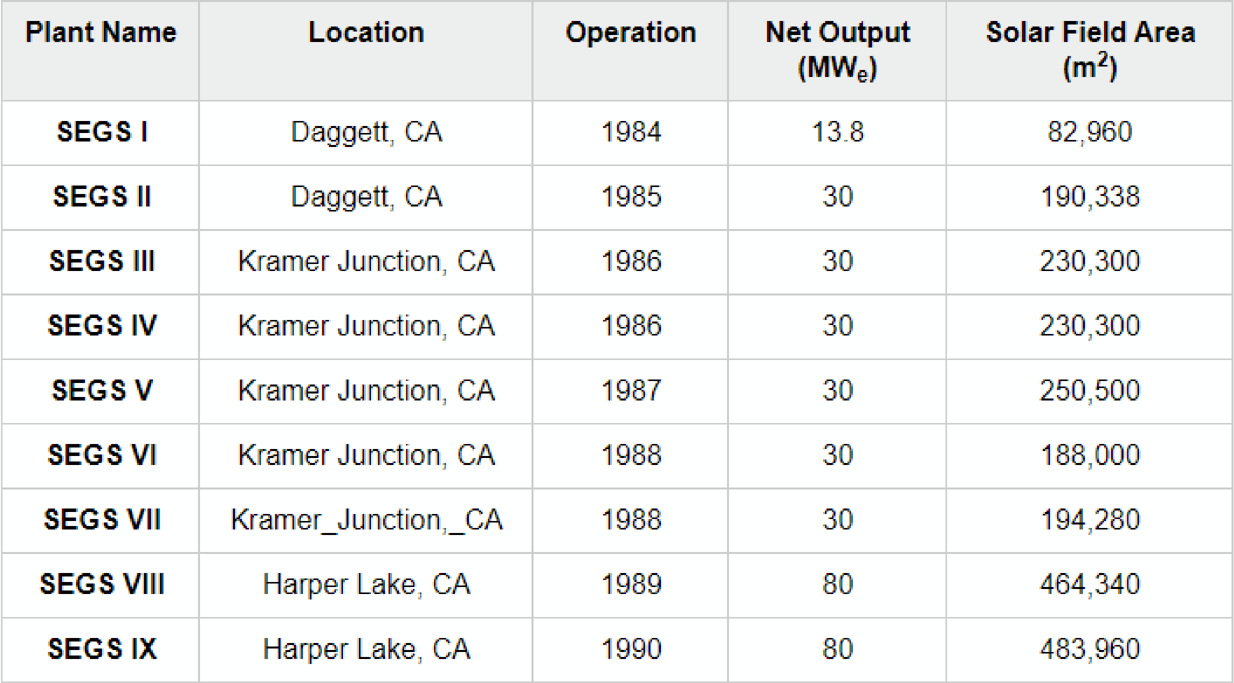


Figure 10: (A)Solar Tower (B)Parabolic Trough (C)Fresnel Reflector (D) Parabolic Dish[34]

Efficiency, and thus cost-effectiveness, of CSP necessitates large, contiguous areas of land in areas with minimal cloud cover. These variables are maximized by building plants 100MW and higher, which is standard practice in implementation. While this constraint would negate viability for microgrid applications, it is still considered for the purpose of comparison. Research is well-funded in this area and technologies are rapidly innovating, so utility is likely to improve.[35]

CSP AS ELECTRICITY

The SEGS project by Luz International Limited, conducted from 1984 through 1991, was the world's first commercial CSP project. Located in the Mojave Desert, the project utilized parabolic trough technology to develop nine power plants, spread over 572 acres, with cumulative net output of 354 MW.[26] Substituting the Mojave average of 6.5 peak sunlight hours[35] into *Eq (1)*, this results in a theoretical hydrogen yield of 91 kg H_2 per acre per day.



Plant Name	Location	Operation	Net Output (MW_e)	Solar Field Area (m^2)
SEGS I	Daggett, CA	1984	13.8	82,960
SEGS II	Daggett, CA	1985	30	190,338
SEGS III	Kramer Junction, CA	1986	30	230,300
SEGS IV	Kramer Junction, CA	1986	30	230,300
SEGS V	Kramer Junction, CA	1987	30	250,500
SEGS VI	Kramer Junction, CA	1988	30	188,000
SEGS VII	Kramer_Junction,_CA	1988	30	194,280
SEGS VIII	Harper Lake, CA	1989	80	464,340
SEGS IX	Harper Lake, CA	1990	80	483,960

Table 3: SEGS Project by Luz International Unlimited[36]

More recently, five solar plants were built between 2013 and 2015 across areas of California, Nevada, and Arizona, as demonstrated in Figure 7. Three of these plants utilize parabolic trough configuration, including Project Genesis and Project Mojave in California and Project Solana in Arizona. The remaining two use power tower configurations and include Project Ivanpah in California and Project Crescent Dunes in Nevada.[26] Cumulative area of these plants is 7,461 acres with total net output of 1,252 MW. Average peak sunlight in these areas is 6 hours,[36] offering a theoretical hydrogen yield of 23 kg H_2 per acre per day.

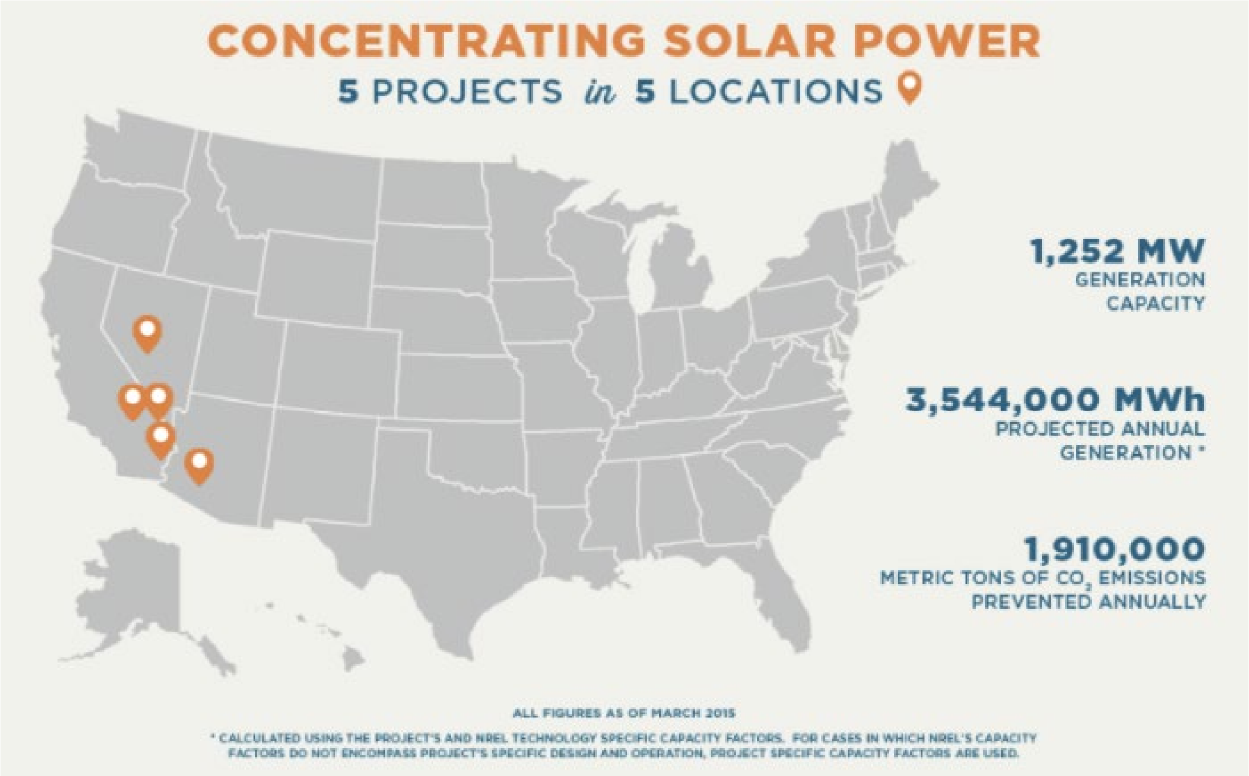


Figure 11: Five Utility-Scale Solar Plants[37]

CSP AS DIRECT THERMAL ENERGY

The Law of Conservation of Energy states that energy can neither be created nor destroyed – only converted from one form into another. There is no known technology to date that converts energy with 100% efficiency; some is lost in transformation, typically released as heat. Ostensibly, using thermal energy to directly drive the generation of chemical potential energy as hydrogen could yield higher efficiency by eliminating electricity as the intermediary energy source. Thus, only one energy conversion would be necessary.

École polytechnique fédérale de Lausanne (EPFL) is testing this hypothesis. A 7-meter parabolic dish prototype was built and tested on campus. The prototype utilizes novel photoelectrochemical (PEC) membrane technology consisting of a proton-exchange solid conductor and semipermeable membrane, coated with iridium-ruthenium oxide nanoparticles to act as a catalyst. Testing of the prototype has yielded 1 kg H_2 per day.[38] With an area of approximately 49 m^2 (530 ft^2), one acre can accommodate around 82 dishes, which *Eq (3)* predicts would yield 82 kg H_2 per acre per day.

Figure 12: EPFL's PEC Parabolic Dish[39]

WIND

Technically a form of solar energy, wind is created by uneven heating of the atmosphere by the sun, surface inconsistencies such as mountain ranges and oceans, and the earth's rotation. Wind is kinetic energy that is converted into electricity by utilizing turbines connected to a generator. Wind energy is abundant, clean, and sustainable. Wind turbines are available in various sizes, allowing for large wind farms and small form factor applications like rural farms and microgrids.[40]

Conventionally, wind farms require large structures with an expansive geographical footprint. However, newer technologies are enabling wind power to be collected at a much smaller scale. The Halo 6kW turbine, for example, is rated at 6.0 kW maximum with a diameter of only 12 ft. This is accomplished using a dual cambered shroud design to maximize airflow, as demonstrated in figure 9.[40]

Figure 13: Halo 6kW Turbine with Dual Cambered Shroud[41]

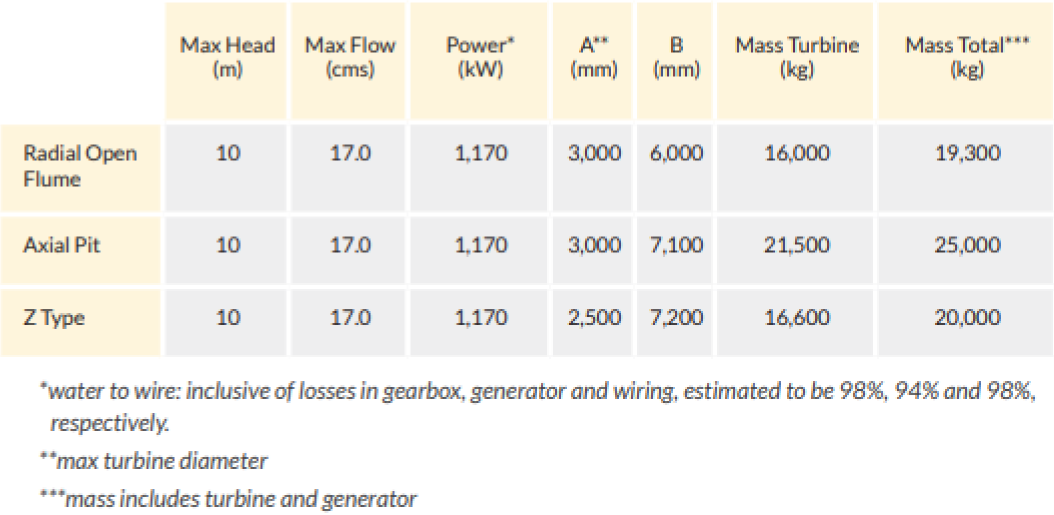
Allotting an area 15 ft wide (225 ft^2) to allow adequate spacing would enable an acre of land to support 193 turbines. Alternating turbine height can also optimize overall collection area. Average wind speed in southern California is 6.9 mph (3.0 M/S)[40], at which the Halo 6kW is rated at approximately 100 watts.[42] Theoretical production utilizing this technology yields 11 kg H_2 per acre per day[Eq (3)]. When compared to other available renewable sources, wind is not viable for application in southern California, but may be advantageous in other geographic locations.

WATER

Utilizing hydropower involves harnessing the kinetic energy of moving water either by diverting a stream through a power collection device, or by strategically placing a dam to force water to collect into a large reservoir that is released slowly through turbine-powered generators. Hydropower can also be stored as potential energy by pumping water from a lower reservoir to a higher one. When power is needed, it is released back to the lower reservoir through spillway turbine generators.[43]

Hydropower technology can have a large geographic footprint depending on reservoir size. Lake Mead, for example, supplies the Hoover Dam and occupies almost 160,000 acres. This system generates an astounding 4 billion kWh of hydroelectric power each year, distributed over areas of Nevada, Arizona, and California serving 1.3 million people.[44] Due to the large reservoir area, however, this correlates to a mere 1.6 kg H_2 per acre per day, if this energy were instead channeled to electrolyzers. This large-scale example does not provide an accurate comparison to microgrid applications.

In contrast, the Buckeye South Extension project by Natel Energy employs a patented low-head modular turbine, requiring as little as five feet of head. This innovation enables installation of a network of hydropower from irrigation canals, existing dams, and natural pathways with minimal impact and footprint.[45] Hydro turbines like Natel's RHT D190 [Table 5] are available in flexible configurations and can be employed in a multitude of cases with minimal footprint by utilizing existing waterflow opportunities. However, this complicates comparison to other renewable sources in terms of output per area and should be considered when analyzing the quantified results of this study. Hydropower provides a viable energy source, independently or synergistically, when application is geographically feasible.



	Max Head (m)	Max Flow (cms)	Power* (kW)	A** (mm)	B (mm)	Mass Turbine (kg)	Mass Total*** (kg)
Radial Open Flume	10	17.0	1,170	3,000	6,000	16,000	19,300
Axial Pit	10	17.0	1,170	3,000	7,100	21,500	25,000
Z Type	10	17.0	1,170	2,500	7,200	16,600	20,000

**water to wire: inclusive of losses in gearbox, generator and wiring, estimated to be 98%, 94% and 98%, respectively.*

***max turbine diameter*

****mass includes turbine and generator*

Table 4: Specifications of Natel Energy's RHT D190 Hydro Turbine[46]

GEOTHERMAL

Geothermal energy is produced using heat from the earth's core. Typically, a well is drilled several thousand feet deep which pumps pressurized hot water to the surface. The pressure is dropped when the water reaches the surface and turns to steam, which powers a turbine to generate electricity.[46]

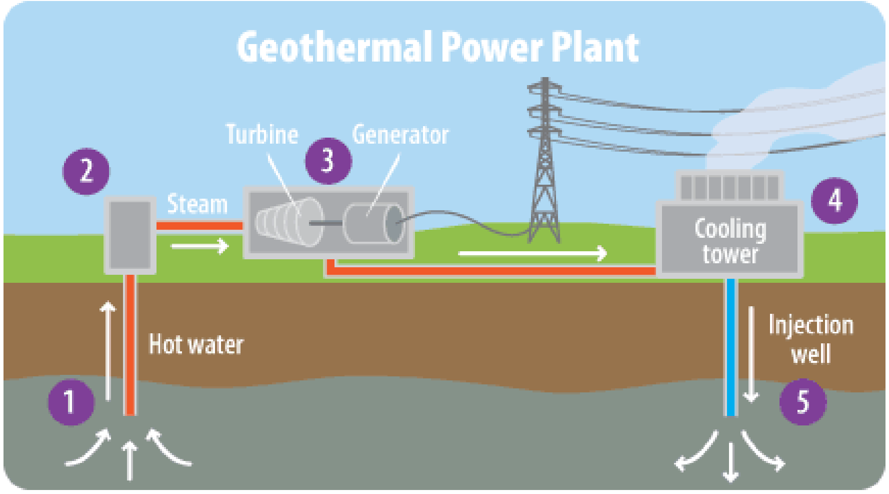


Figure 14: Geothermal Energy[47]

The biggest disadvantage of geothermal energy is the geographical requirements involved. Of all the United States, California has the largest capacity for geothermal power generation due to proximity to the ring of fire, a stretch of almost 25,000 miles of active volcanoes and earthquakes. California is home to over 40 geothermal power plants and produces over 5% of California's power.[48]

Figure 15: Pacific Ring of Fire[49]

Geothermal energy has quite a small footprint compared to other renewable energy sources. The powerplants require 12% less area than solar PV and 30% less area than wind. California Energy Commission estimates that geothermal powerplants net from 55,000 to 600,000 MWh in 2019.[50] Using the low end of 55,000 MWh, about 350 kg H_2 can be produced per day. Hydrogenics Corporation, a Canadian company, has plans to install a 1.5 MW hydrogen production facility in New Zealand this year.[51] Geothermal energy can produce enormous amounts of hydrogen and is an area of interest to consider for future work.

BIOHYDROGEN

Utilizing bio-enzymatic pathways of microorganisms offers an eco-friendly and sustainable method of hydrogen production. Novel techniques utilizing a variety of organisms have been and are currently being studied and refined, most of which are categorized as either fermentation or biophotolysis. Production yield varies among these approaches, and each has unique constraints. Challenges to commercial and industrial application include intolerance to oxygen (a byproduct of hydrolysis), relatively low yields, and accumulation of metabolites. Until these barriers are overcome, biohydrogen is not feasible at scale. However, enabling this production method is a major focus of many current research projects.[51]

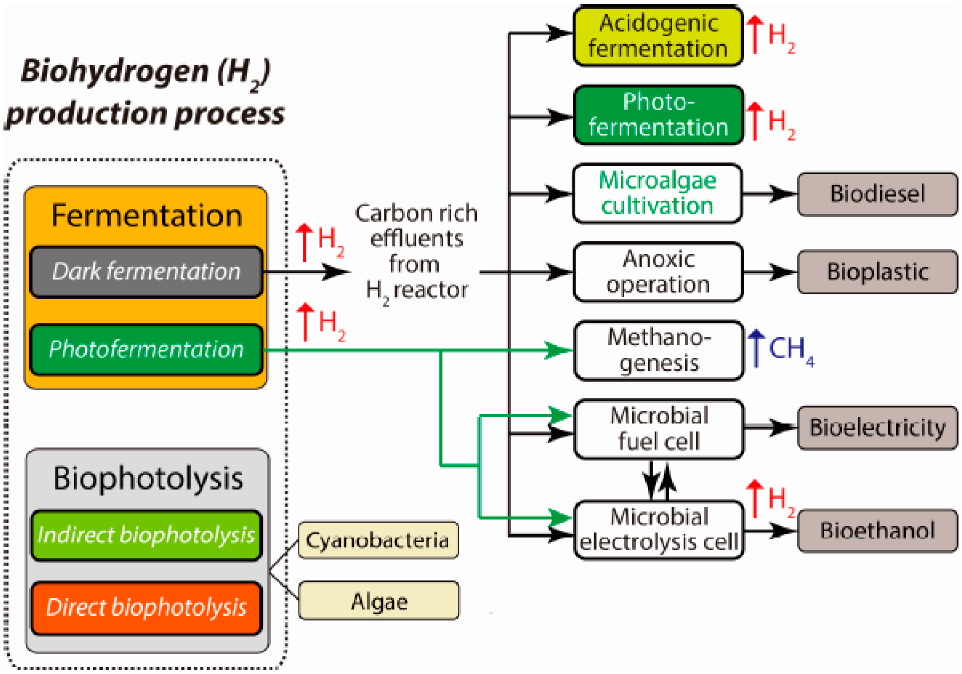


Figure 16: H_2 Production - Primary Biological Routes with Secondary Processes[51]

Fermentation processes utilize glycolytic pathways and can be accomplished by several different organisms. Species facilitating this process may be autotrophic, heterotrophic, aerobic, or anaerobic, offering variability in environmental requirements. Glycolysis for hydrogen production enzymatically degrades sugars into hydrogen and other metabolites. Products are dependent upon the specific pathway involved, though many pathways include carbon dioxide and carboxylic acids as byproducts.[51]

Biophotolysis involves splitting water by photosynthesis. Hydrogenases and nitrogenases synthesized by various green microalgae and cyanobacteria cooperatively catalyze this process. Depriving these organisms of sulfur causes a metabolic shift from oxygenic photosynthesis to a hydrogen-producing process, thus increasing production yield and efficiency.[52] Another approach is to integrate oxygen-tolerant enzymes from anaerobic species, such as *Clostridium acetobutylicum* or *Rubrivivax gelatinosus*, into photosynthetic species to overcome oxygen sensitivity.[53]

CURRENT ON-SITE HYDROGEN PRODUCTION

In Golden, Colorado, the National Renewable Energy Laboratory (NREL) is developing on-site hydrogen production technology to support heavy duty trucks. Hydrogen demands for these trucks are comparable to that of eVTOLs. Ostensibly, if on-site hydrogen production infrastructure is feasible for trucks then it would also be for eVTOLs. NREL is utilizing water electrolysis technology as discussed previously. Electricity is generated from renewable sources then used to power an electrolyzer.[53]

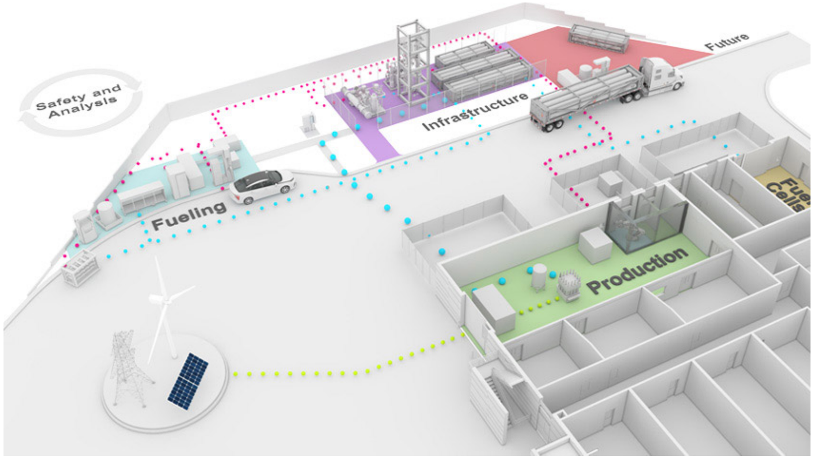


Figure 17: On-Site Hydrogen Production at NREL [38]

In Lausanne, Switzerland, École polytechnique fédérale de Lausanne (EPFL) has developed a CSP system using a parabolic dish that produces 1 kg of hydrogen per day. Because it uses direct thermal energy, this system does not require power generation or storage. The project was so successful that it has spun out into its own company called SoHHytec,[54] who has received over $1M in grants for ongoing product development.

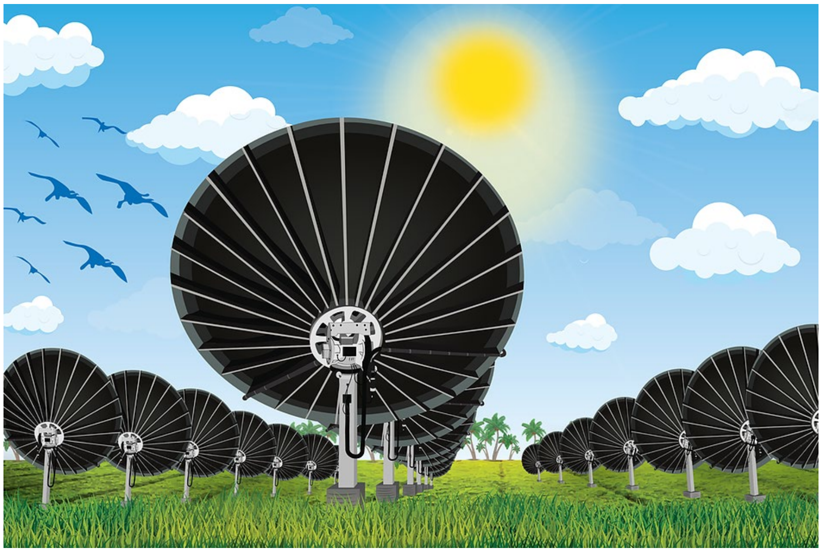


Figure 18: Hydrogen Farm Using Parabolic Dishes [55]

Organizations like NREL and SoHHytec leverage both electrolyzing water and concentrating solar technologies, respectively. The key difference between the two being necessity of electricity and utilization of electrolyzers.

CONCLUSION

The State of California is a potential candidate for captive use hydrogen in air taxi and heavy-duty truck infrastructure. Table 5 represents the viability of various renewable sources that can produce hydrogen at a microgrid scale.

	kg H_2	Contraints	Viability
PV: HE Flat Plate	116	Efficiency, Location Specific	🟨
PV: Cylindrical	202	Developing	🟩
CSP Electricity	91	Large Area Requirement	🟧
CSP Direct Thermal	82	Large Area Requirement, New	🟨
Wind	11	Extremely Inefficient	🟥
Water	1.6	Inefficient, Terrain Dependent	🟥
Geothermal	350	Extremely Location Specific	🟩
Biohydrogen	NA	Developing	NA

Highest 🟩
🟩
🟨
🟨
🟧
🟧
Lowest 🟥

Table 5: *Viable Renewable Energy Technologies in California*

The most favorable options include HE flat plate[1], PV[2] cylindrical, CSP direct thermal[3], and geothermal. CSP direct thermal may have the most promising future potential, using parabolic dishes or troughs, as this method of hydrogen production does not need to generate or store electrical power.

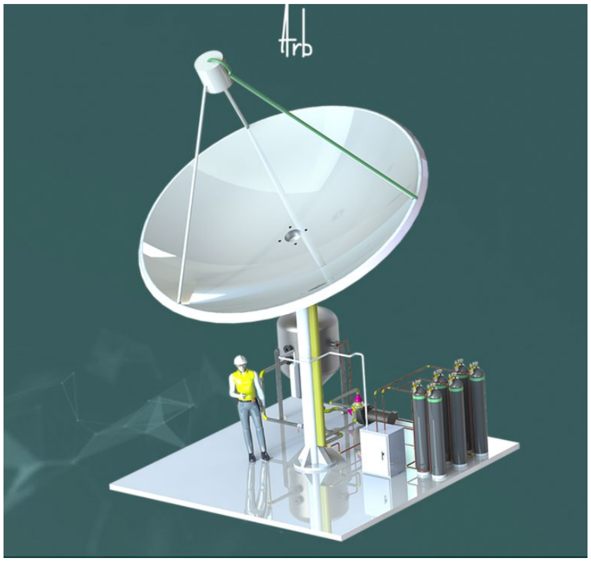


Figure 19:CSP Direct Thermal [56]

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[1] High-efficiency flat plate solar panels

[2] Photovoltaic cylindrical solar panels

[3] Concentrated solar power using parabolic dishes or troughs

Symbiotic combination of different sources is ideal, as the technologies would not compete for resources. For example, geothermal technology resides underground, while the area above remains available for solar collection devices. Wind and water show minimal viability in this study, though they may offer additive benefit in certain terrains.

Analysis of hydrogen fuel cost may include investigation of current production methods using both fossil fuels and renewable energies and determining a competitive price point for new technologies. Solar-rich states like California often accrue energy in such abundance that it overloads grid capacity,[24] while other states have experienced overload with wind farms. There may be significant opportunity to utilize this superfluous energy to produce hydrogen**. A cost comparison of power generation to make hydrogen (using sun, wind, etc. as discussed above) at the refueling station versus offloading excess power from an existing utility company should be conducted.**

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