CHAPTER 11
HYDROGEN ENERGY STORAGE

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Abstract

As states with clean energy mandates push for more renewable sources of energy, the need to store large amounts of energy for long periods (days to months) will increase. One possible solution is to use excess energy from renewable generation in an electrolyzer to produce hydrogen that can be stored in large quantities using inexpensive gas storage methods and used in fuel cells or combustion generators to produce electricity as needed. As hydrogen has additional benefits outside of the electric grid, a hydrogen-based energy storage system could be the connection point to other energy sectors currently dominated by fossil fuels. However, challenges related to upfront costs for electrolyzers and fuel cells, hydrogen distribution, roundtrip efficiency, and safety remain. This chapter discusses the potential role that hydrogen storage could play as a grid asset, relevant trends surrounding hydrogen technologies, and the remaining impediments to widespread hydrogen energy storage use.

Key Terms

Electrolysis, electrolyzer, flexible fuel hydrogen, fuel cells, long duration storage, proton exchange membrane (PEM), steam methane reformation (SMR)

1. Introduction

Though the exact configuration of any electric grid with a high renewable penetration is difficult to predict, studies have been performed for several regions around the world that show some common trends.

Studies focused on 100% renewable grids that minimize the renewable generation capacity have predicted that staggering amounts of energy storage will be needed to balance supply and demand. Analysts have predicted energy storage needs of 30 TWh or more in California [1], 40 TWh or more in Japan [2], and 200 TWh or more in Europe [3] to operate their electric grids without wasting any solar generation. These levels of storage allow for excess renewable generation created during peak seasons of the year to be used during low solar production seasons. Though Li-ion batteries currently account for the majority of non-hydro grid-scale storage installations, the potential to scale these batteries to systems in the tens or hundreds of TWhs cost-effectively is limited. Based on the 2019 United States Geological Survey, there are about 62 million tons of Li resources worldwide [4]. At 120g Li/kWh of storage [5], that is enough lithium to provide approximately 470 TWh of storage on the entire planet. All of these factors suggest that other solutions should come into play to reach 100% renewable goals, either to reduce storage needs or to use less expensive storage technologies based on more abundant materials.

The studies mentioned above include a key assumption that necessitate such large quantities of energy storage, namely that all renewable energy produced is either used directly by end users or is stored for later use to minimize the installed renewable generation capacity. In other words, renewable power cannot be wasted. However, given the rapidly declining prices of renewable generation technologies, this is not the most cost-effective solution. Studies that focus on *minimizing the cost* of energy systems based on renewable generation and energy storage [6] [7], rather than minimizing the amount of renewables that are installed, show that installing *extra* renewable generation leads to *much* lower overall system costs. In fact, some work has suggested that making two or three times the amount of annual energy demand would greatly reduce the overall system cost as less energy would need to be stored. However, even though the system costs would be lower, wasting two-thirds of the energy generated by a system would represent a large amount of lost revenue if the excess generation was not used in some fashion

Of course, many factors that could change the results of the predictions mentioned above. Transmission networks could be expanded, system loads could become more flexible, and certainly technologies and market costs are continuing to evolve, but the trends revealed by system planning studies are still relevant. It is likely that grids approaching 100% renewable penetration will need to incorporate large amounts of storage and/or produce excess renewable generation regardless of the exact configuration. The probable combination of large quantities of storage and excess renewable generation makes energy storage based on hydrogen an attractive option because of the unique capabilities and flexibility associated with hydrogen fuel. There are many options to store hydrogen in large quantities inexpensively and the multitude of uses for hydrogen once it is produced that make it a good sink for extra generation. This chapter discusses how hydrogen energy storage can positively affect grid operations and why it should be considered in long-term planning, while highlighting challenges and mitigation strategies.

2. State of Current Technology

Hydrogen can be considered an energy storage medium in the same way other chemical fuels store energy (i.e., in the chemical bonds that make up the molecules). At standard temperatures and pressures, hydrogen exists as a gas similar to natural gas (i.e., methane), and can be stored by established gas storage methods such as in tanks or underground caverns. One dramatic difference between hydrogen and natural gas is that pure hydrogen does not occur naturally and must be separated from compounds that contain it. The current commercial feedstocks for hydrogen production are typically hydrocarbons, but nitrogen compounds such as ammonia can also be used. To consider hydrogen as an *electrical* energy storage technology, in which the system is connected to the power grid, additional components are needed to convert between the chemical and electrical forms of energy. The system would need to consist of 1) an electrical hydrogen production device, 2) a hydrogen storage unit, and 3) a device to generate electrical energy from the stored hydrogen, along with the requisite power conversion and control equipment (Figure 1).

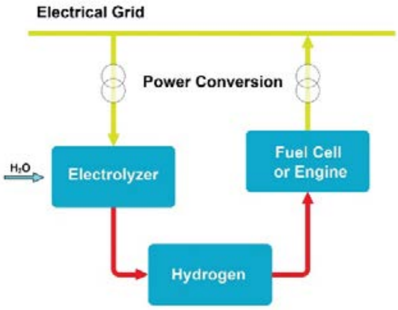
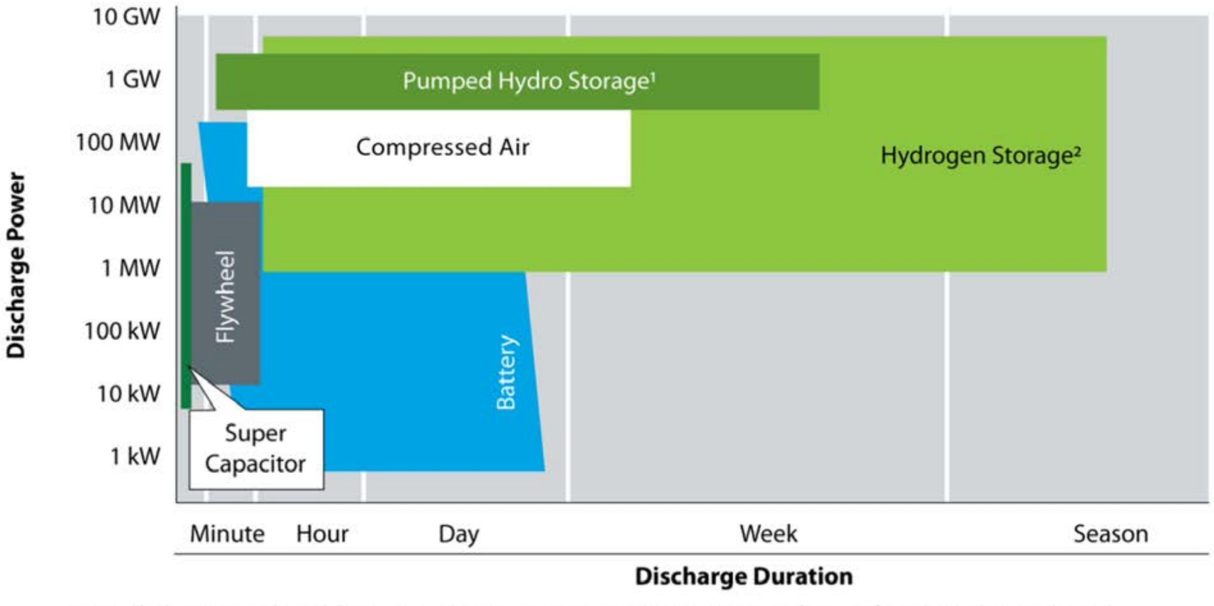


Figure 1. Concept of hydrogen electrical energy storage where power is drawn from the grid and returned to the grid. Alternatively, the electricity can be drawn from a standalone renewable power source and delivered to a standalone electric load

Conceptually, off-peak or excess energy would be used to produce hydrogen, which can be stored for very long periods with minimal losses. The stored hydrogen would later be used to generate electricity as needed. This combination of systems to produce, store, and use hydrogen is one of the few options with the potential to store large capacities (up to TWh) of energy for long periods such for months between seasons. Large scale thermal energy storage as discussed in *Chapter 12, Thermal Energy Storage Technologies* is another option to consider and has similar pros and cons to hydrogen-based energy storage. Both methods are useful for their scalability and storage efficiency (barring gas leaks or significant thermal losses) but suffer in terms of roundtrip efficiency and cost.

The roundtrip efficiency of hydrogen storage based on electrolysis and fuel cell systems is generally around 40%, meaning that approximately 40% of the energy used to produce hydrogen with electricity can be turned back into electricity. This is somewhat low as compared to 70-90% for Li-ion battery storage, though laboratory hydrogen systems have demonstrated efficiencies as high as 50% [8]. Furthermore, the power components associated with hydrogen systems are generally much more expensive than other storage options. However, the amount of energy that can be stored with hydrogen can easily be expanded by increasing the size of the tanks or reservoirs being used, which is inexpensive. As such, despite the lower efficiency and high up-front cost, if large amounts of energy need to be stored, hydrogen is ultimately a cheaper storage option than batteries. Figure 2 shows a comparison of the optimal power and duration characteristics for various energy storage options. This shows that hydrogen is a suitable option if large quantities of energy need to be stored for long periods of time.



[1] Pumped hydro capacity is limited due to geographic constraints. Estimated maximum potential is <1% of U.S. electrical energy demand

[2] As hydrogen, ammonia, or synthetic natural gas

Figure 2. Battery and hydrogen storage cost comparison versus duration [9]

While the $/kW price of a hydrogen energy storage system would be high, as the amount of energy required increases, the relatively low $/kWh price of hydrogen makes the overall system cost less with high duration needs. A preliminary study has estimated that hydrogen-based storage is less expensive than battery energy storage for storage durations greater than approximately 13-15 hours at current component prices [10].

Other attributes make hydrogen an attractive energy carrier. Firstly, hydrogen can be used for many applications outside of the electric grid. Transportation, heating and industrial processing, all areas that currently served almost entirely by fossil fuels, all could run on hydrogen. As such, hydrogen production could allow electricity producers to use excess renewable generation to maximize profits by selling a valuable and flexible product or service to a new and much wider customer base. Secondly, hydrogen use could be expanded significantly and sustainably. Hydrogen storage systems are mostly based on widely available materials, and at GWh to TWh scales of storage, this is a significant consideration for long term planning. The most limiting materials needs are the active catalysts that typically use precious metals (platinum, palladium, etc.), which are used for some electrolyzers and fuel cells. The available resources for these metals are either expensive or limited in some cases, but there are various methods to recover in excess of 95% of the active materials [11]. Work is also ongoing to limit or eliminate the need for precious metal catalysts, which would further improve the sustainability of hydrogen-based energy storage. Last, hydrogen is a non-toxic, non-greenhouse gas, meaning that hydrogen leaks are a relatively small environmental concern compared to other gases used today.

The following sections will cover the requisite components of a grid-connected, hydrogen-based energy storage system in more detail.

2.1. Hydrogen Production

Hydrogen has been produced from hydrocarbons such as methane or natural gas for decades for use in various industrial and research applications. This is typically done by reacting hydrocarbons in the presence of steam at high temperatures, leading to the generation of carbon monoxide, carbon dioxide, and hydrogen in a process called steam methane reformation (SMR), as shown in Equations 1a and 1b.

$$\begin{aligned} CH_4 + H_2O(+\text{heat}) \rightarrow CO + 3H_2 \quad &(\text{a}) \\ CO + H_2O \rightarrow CO_2 + H_2 \quad &(\text{b}) \end{aligned} \tag{1}$$

Some complex systems include both heat and electricity, but conventional SMR requires a two-step chemical process. Another option for hydrogen production is electrolysis, a process that uses electrical energy to split purified water into oxygen and hydrogen in an electrolyzer. Electrolyzers use catalysts to enable the water-splitting reaction shown in Equation 2.

$$2H_2O_{(l)} + \text{energy} \rightarrow O_{2(g)} + 2H_{2(g)} \tag{2}$$

Electrolysis requires a pure water source to produce hydrogen, but all commercial electrolyzers include a water purification step to allow a wide array of water sources to be used. University analyses have shown that resource availability is not a concern in any of the locations currently installing or considering the installations of electrolyzers, even for large-scale operations. Ultimately, all the hydrogen consumed, either in fuel cell vehicles, fuel cell power plants or turbine power plants is emitted as water. In some instances, the water could be captured and reused.

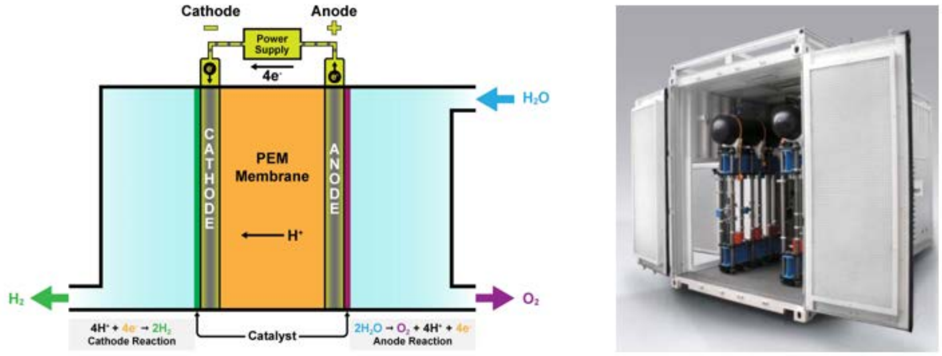
While both electrolysis and SMR have been used for decades, SMR has been more common for large-scale production of hydrogen because it is less expensive than electrolysis given the low cost of natural gas and is less energy consumptive. However, SMR generates carbon emissions, so it is not ideal, especially in areas with low-carbon energy goals. In recent years, manufacturers of electrolyzers have made tremendous strides to decrease system costs and increase the scale of useful production for the energy storage market. Furthermore, low mid-day electricity prices, due to the increase in solar generation in some areas and excess wind power in others, is beginning to make hydrogen production from electrolysis cost competitive with SMR on a $\$/kgH_2$ basis. Given the synergy of electrolysis with renewable generation, this mode of hydrogen production is the focus in this chapter.

2.1.1. Electrolyzers

Two types of low-temperature electrolyzers, based on two different water dissociation approaches, are commercially available for bulk hydrogen production: alkaline electrolyzers and proton exchange membrane (PEM) electrolyzers. Either technology can be used for energy storage application.

Alkaline electrolyzers have been sold for nearly a century and are generally used for industrial hydrogen production. This type of electrolyzer operates with two electrodes immersed in an alkaline electrolyte solution of potassium hydroxide or sodium hydroxide. A DC current applied across the electrodes causes the dissociation of water, and an ion exchange membrane separating the electrodes causes the hydrogen and oxygen molecules to be released separately. The alkaline electrolyzer may be less expensive but handling of the caustic electrolyte solutions during maintenance operations may be a deterrent to some.

PEM electrolyzers use a solid electrolyte, thereby avoiding the use of caustic solutions that can be harmful to skin or lungs. These electrolyzers also tend to be more efficient and can vary their hydrogen production rates (i.e. vary their electricity consumption) more quickly than alkaline electrolyzers. PEM electrolyzers are being used more than alkaline because of their ability to operate in response to control signals (e.g., performing frequency response or photovoltaic smoothing operations for grid applications). A schematic of a PEM electrolyzer and a photograph of a small PEM system manufactured by Proton On-site are shown in Figure 3. A large-scale electrolysis plant (1MW) is shown in Figure 4. Several companies are currently planning the installation of electrolyzer systems as large as 50 MW for use in the production of hydrogen fuel and for energy storage applications.



(a) (b)

Figure 3. PEM Electrolyzers – a) schematic [12] and b) Proton on-site electrolyzer

Figure 4. ITM Power 1 MW electrolyzer

The major challenge for electrolytic hydrogen production is cost. Although capital costs have been decreasing dramatically in recent years, PEM electrolyzers are still expensive ($740/kW) [10]. It is estimated that prices could reach approximately $250/kW in the future through improvements in membrane design, materials, and mass production [10]. System reliability and lifetime, which were points of concern in the past, have improved in the last decade as well, and run times in excess of 100,000 h are now possible [13].

Solid oxide electrolyzers, which operate at much higher temperatures than other electrolysis technologies (650-1000°C), are also being developed. These have the potential advantages of higher efficiency without the use of expensive catalytic materials given their high temperature operation. The elevated operation temperature reduces efficiency losses associated with the dissociation of hydrogen and oxygen molecules and allows high conversion efficiencies to be reached. However, these systems do not respond as quickly as PEM electrolyzers and high degradation rates are a concern. These systems are currently at the laboratory/demonstration phase, though a few companies are trying to bring them to market [14].

Beyond the system cost, the cost of the hydrogen produced depends directly on the cost of the electricity used to generate it. Negotiations or market tariffs with electricity generators to use excess renewable electricity could lower hydrogen production costs, and in some cases hydrogen could be eligible for tax incentives as a low-carbon fuel. Hydrogen directly paired with renewable installations to utilize excess electricity is also promising, particularly if those installations are or will be frequently required to curtail output. Lastly, research is ongoing to improve the efficiency of electrolysis through catalyst and balance-of-plant improvements. Currently, electrolyzers convert about 70-80% of the input electrical energy into hydrogen.

2.2. Hydrogen Storage and Distribution

Once generated from electrolysis or another production method, hydrogen can be stored in gaseous, liquid, or bound (e.g. chemical) states. Methods for storage currently being used or researched are high-pressure gas tanks, cryogenic liquid tanks, gas pipelines, geologic storage in salt caverns, adsorption in metal hydrides, and bonding with liquid organic hydrogen carriers (LOHCs). Each form of storage has advantages and disadvantages in terms of space requirements, cost, and transportability. Table 1 summarizes some of the characteristics of the storage options.

Table 1. Hydrogen Storage Technology Characteristics

Parameters	Cryogenic liquid [14]	Compressed gas [14]	Pipeline [15]	Salt cavern [16]	Hydrides [17]	LOHC [18]
Commercial status	Available	Available	Some, near refineries	Limited to industrial suppliers	Available	In development and trial
Storage scale	15,000 kg	1,000 kg	NA	8,000,000 kg	20 kg	5,000 kg
Transport Scale	4000 kg	300 kg	LAX area: 17 miles	NA	5-10 kg	10,000 kg
Barriers	Cost	Cost	Material impact	Geological suitability	Storage & release, cost	Cost, scale

2.2.1. Compressed Gas and Liquid Storage

High-pressure gas or cryogenic liquid containers minimize the volume of storage. These typical approaches are well established as they differ very little from the storage of any other industrial gas. The technologies for both approaches are currently available in the commercial marketplace. Compressed gas tanks for vehicles typically come in standard pressures of 250 bar (3,600 psi), 350 bar (5,000 psi) or 700 bar (10,000 psi), and the development of tanks for vehicles is also reducing the cost of high-pressure storage for stationary applications. Cylinders carrying compressed hydrogen gases are shown in Figure 5. Design and material research is ongoing to make high-pressure gas containment more affordable. This has the added benefit of increasing the energy density of the storage system. However, gas compression can be energy intensive, so storage at lower pressures should be considered if the system volume is not a major concern. Current price estimates (in 2020) for gaseous hydrogen storage are around $35/kWh.

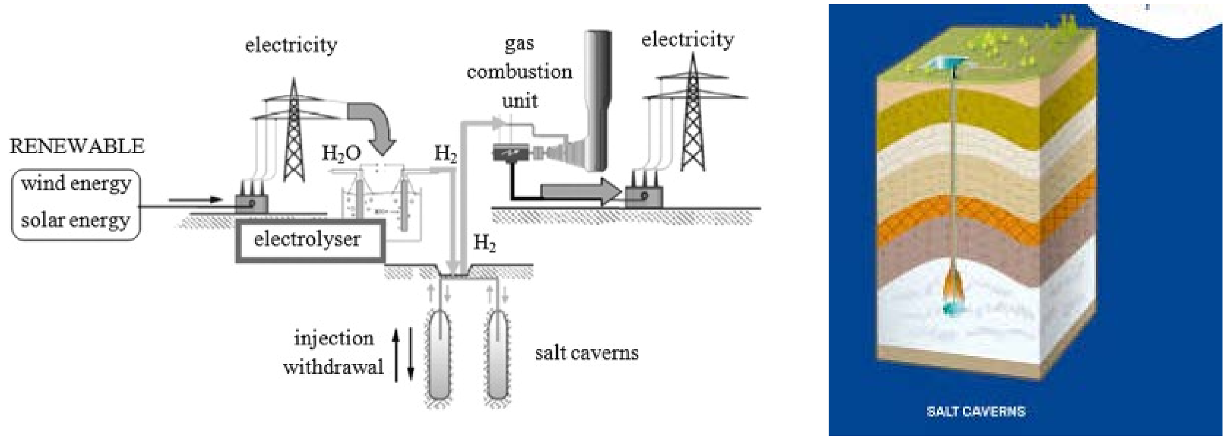
Figure 5. Photo of hydrogen gas cylinders on a tube trailer [15]

Hydrogen can also be stored as a liquid for many applications. Cryogenic liquid hydrogen is stored at 20K (−423°F; −253°C). Liquefying hydrogen further increases the volumetric energy density hydrogen, but it requires a considerable amount of energy to cool hydrogen to such low temperatures, which reduces the roundtrip storage efficiency. Furthermore, over long periods of storage time, the system would be particularly susceptible to boil-off losses due to unavoidable ambient heating of the liquid. Recent cryogenic design advancements have reduced the rate of heat transfer and resulting hydrogen loss, but it is still not ideal for storing hydrogen for long periods of time. This typically makes liquid hydrogen an undesirable storage method for long-duration grid applications, but it is relevant for transportation of hydrogen from production facilities to load centers. Cryocompression is a newer approach to mitigate boil-off losses in hydrogen systems. In cryocompressed storage, a high-pressure tank is modified to operate at liquid nitrogen temperatures (about 77 K). The higher operating pressure significantly improves the tank “dormancy” (the time to hydrogen release from the tank), and also permits near liquid-like densities at 77 K without having to reduce the temperature all the way down to liquid hydrogen temperatures.

2.2.2. Underground Hydrogen Storage

In addition to manufactured containers, gas pipelines and geologic storage are attractive methods for storing large volumes of hydrogen. Hundreds of miles of pipelines carrying pure hydrogen are near refineries in south Texas and Southern California. Unused or abandoned pipelines could make excellent storage vessels, depending on the material of which they are made. A number of studies have recommended new pipelines as economically feasible for both long and relatively short distances [16]. The blending of hydrogen into existing natural gas pipelines is discussed later in this chapter.

Geologic storage refers to the use of underground caverns to store large volumes of gas. Although rock caverns, aquifers, and abandoned mines have been considered for this purpose, the most viable caverns for hydrogen are created by solution mining in salt deposits. This results in large, impermeable salt caverns deep underground. The petroleum and chemical industries use underground salt caverns to store hydrogen, natural gas, and other fuels near refining operations. Similar to the proposed use case for grid-scale hydrogen storage, these caverns are often used to help to rectify the variable consumption of natural gas throughout the year with the constant production rate from refineries. Figure 6 shows a diagram of such a hydrogen storage system for grid energy storage.



(a) (b)

Figure 6. a) Potential use of geologic storage of hydrogen and b) Sketch of salt cavern storage [17]

Hydrogen storage in geologic formations requires careful siting to limit stability concerns, however, the requisite salt deposits are not available everywhere. Sandia has published maps showing suitable locations in *A Life Cycle Cost Analysis Framework for Geologic Storage of Hydrogen: A User's Tool* [18]. Although geologic hydrogen storage may have limited siting locations, this mode of storage is incredibly inexpensive ($0.08/kWh) for very large storage capacity, making it an attractive storage option. As described later, the most efficient integrated system will locate the power generation unit near the storage site and transmit power using new or existing wires.

Hydrogen can also be stored in the chemical bonds of various compounds. Solid materials such as metal hydrides are sometimes used. In these systems, a metal (M) absorbs hydrogen (H) to form a metal hydride (MH). Hydrogen can then be released by heating the MH as needed. These materials increase the volumetric energy density of the storage system even beyond that of liquid hydrogen. These systems also offer increased safety because they operate at lower pressures and the release of hydrogen is slowed by desorption processes in the event of a leak [19]. Some metal hydride storage devices are commercially available and are suitable for relatively small amounts of hydrogen. Research on material stability and improving the kinetics of hydrogen release is ongoing to make grid-scale storage possible

2.2.3. Carrier Material Storage

Liquid organic hydrogen carrier (LOHC) materials such as methylcyclohexane provide another way to store hydrogen. These energy rich liquids can be easily stored and transported without the need for cryogenic temperatures as with liquefied pure hydrogen. Hydrogen can then be released from the LOHC for use through dehydrogenation processes. Figure 7 shows one approach to hydrogen transport using LOHCs being demonstrated in Japan. Japan has a national plan for a clean hydrogen economy but limited renewable resources. The LOHC project is intended to showcase the potential to transport large volumes of hydrogen internationally using LOHCs to support the country's hydrogen vision. The first shipment of hydrogenated LOHC was successfully shipped to from Brunei to a dehydrogenation plant in Japan in December 2019 [20].

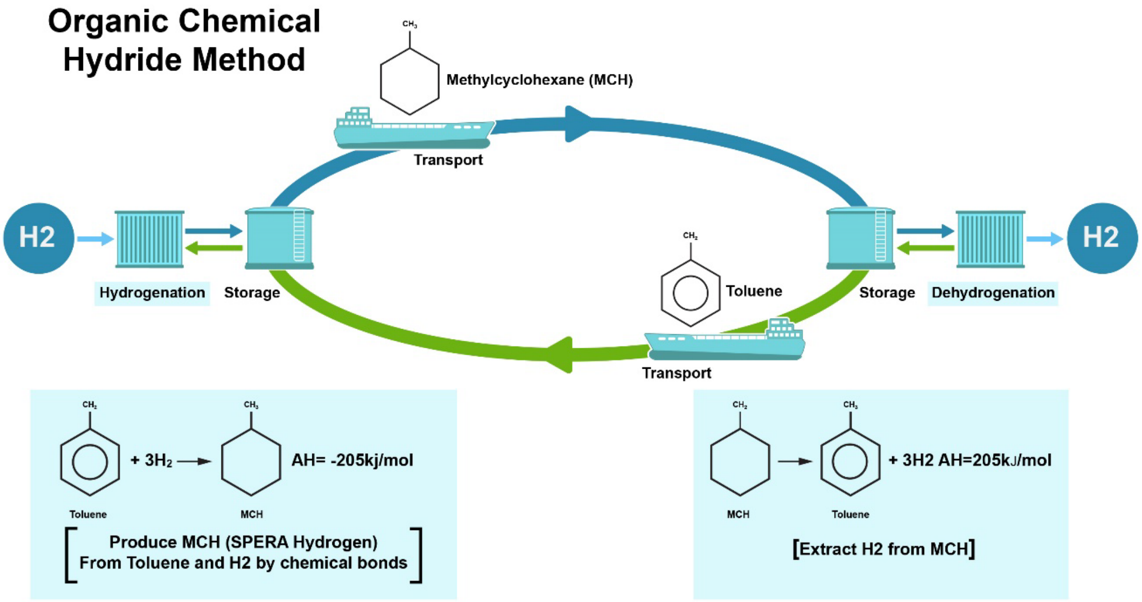
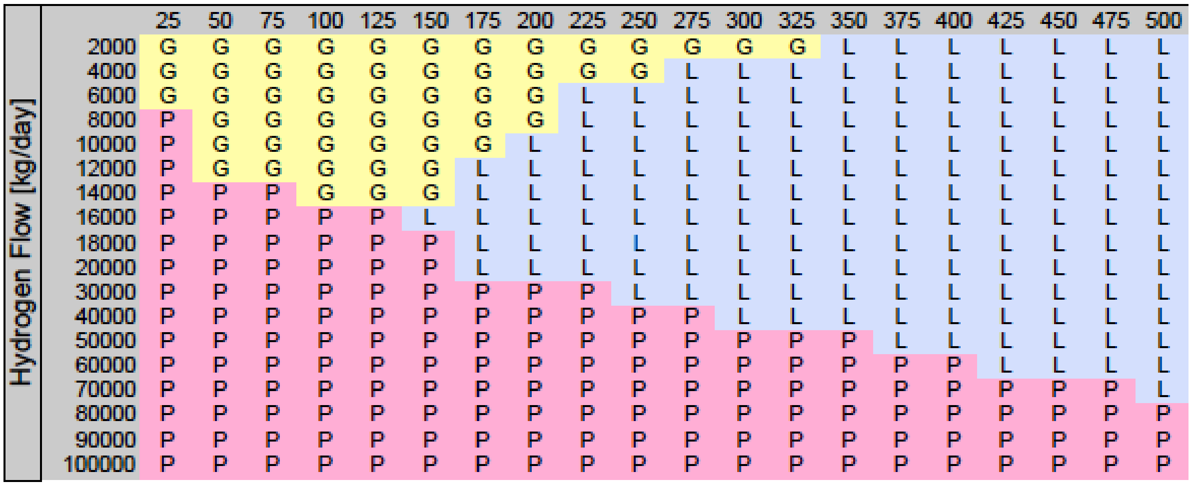


Figure 7. Concept for large hydrogen transport using LOHC [21]

2.2.4. Hydrogen Storage Selection

Several studies have compared costs for different modes of hydrogen storage, which depend in large part on the mass to be stored. For example, cryogenic liquid storage can be less expensive per kg than compressed gas storage if more than approximately 500 kg needs to be stored. Similarly, salt cavern storage is promoted as particularly inexpensive, but is only useful for enormous amounts of storage (greater than about 8,000,000 kg or 8,000 tonnes) because a significant fraction of the cost comes from drilling the well and handling the brine for the solution mining process; activities that do not scale with the size of the cavern. Once established, the marginal cost of increasing the size of the cavern is the attractive feature of geologic storage.

Additional studies have compared the cost of transporting hydrogen, which also depends on how much mass and how far the hydrogen needs to be transported. A useful chart from a UC Davis study is shown in Figure 8. As suggested by the Figure, smaller amounts of hydrogen being transported shorter distances would be effectively transported as gas, while greater amounts are transported as liquid. If available, pipeline transport would be preferred for most amounts and all distances.



Hydrogen Flow [kg/day]	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
2000	G	G	G	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L
4000	G	G	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L
6000	G	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
8000	P	G	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L
10000	P	G	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L
12000	P	G	G	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
14000	P	P	P	G	G	G	L	L	L	L	L	L	L	L	L	L	L	L	L	L
16000	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
18000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
20000	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L	L	L	L
30000	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L	L	L
40000	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L	L	L	L	L	L
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60000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L	L	L	L
70000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	L
80000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
90000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
100000	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

Figure 8. Mode map describing the lowest-cost hydrogen delivery options as a function of hydrogen flow and transport distance (km). [G]. [L] and [P] indicate compressed gas, liquid trucks and pipelines, respectively. [22]

2.3. Power Generation Using Hydrogen

To generate electricity from hydrogen, it needs to be reacted with oxygen and the resulting energy captured and used by an electric generator. The simplest form of this reaction is combustion:

$$2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(l)} + \text{energy} \tag{3}$$

where oxygen and hydrogen combine to produce water and release energy in the process. As a result, the only direct emission from a hydrogen-based power unit is clean water. Two main classes of technologies are used for power production from hydrogen: fuel cells and hydrogen engines. Fuel cells directly use the reaction energy in an electric circuit, while hydrogen engines combust the fuel and produce electricity with a conventional generator. Both means of electricity production using hydrogen are described in the following sections.

2.3.1. Fuel Cells

As with electrolyzers, different types of fuel cells are available. For applications with changing loads, the PEM fuel cell is preferred because of the ability to operate responsively under varying conditions. A schematic of a PEM fuel cell is shown in Figure 9. A PEM fuel cell reverses the activity of a PEM electrolyzer, combining hydrogen and oxygen to produce electricity. In most fuel cell systems, air is pumped into the system as the source of oxygen for the reaction. The nitrogen and other components in the air are considered diluent and reduce the maximum possible efficiency. Some specialized systems, such as spacecraft, use purified oxygen as the source to maximize efficiency, but this would not be the common approach for a stationary, grid-tied system.

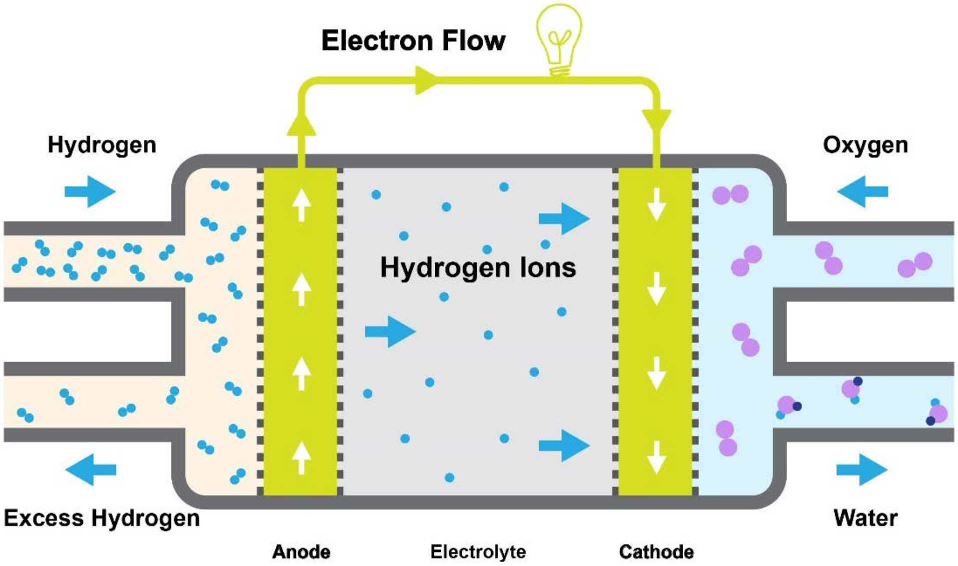

Figure 9. Electricity generated in a fuel cell

Multiple companies offer PEM fuel cells commercially for vehicle or stationary use. The 1 MW fuel cell shown in Figure 10 has been used in Honolulu to provide power for refrigeration units (“reefers”) used to keep cargo cold during intra-island transit. Sandia National Laboratories sponsored the Maritime Hydrogen Fuel Cell project to test a hydrogen-fuel-cell-powered generator as an alternative to conventional diesel generators [23]. The largest PEM fuel cell systems are typically composed for 1-2 MW modules, integrated up to sizes of multi-megawatts.

Figure 10. Fuel cell stationary power plant

Other types of fuel cells include the solid oxide fuel cell (SOFC) and the phosphoric acid (PA) fuel cell. Currently, these technologies typically use natural gas as the fuel source and include a subsystem that generates hydrogen from the natural gas by reformation, though some systems exist that can use hydrogen directly. More companies are working to make it possible for their SOFC and PA products to operate on hydrogen, and a few such options are commercially available. Currently, the largest PA fuel cell power plant running on hydrogen is a Doosan system operating in South Korea [24]. The source of hydrogen is by-product gas from a petrochemical plant. Having eliminated the reformer from their standard product, Doosan is now making this version of their fuel cell power plant commercially available.

Challenges do remain with regards to widespread fuel cell use however. The major challenge for PEM fuel cells is, again, cost (currently approximately $500/kW, with a future estimate of $250/kW) [10]. This cost is largely due to the catalysts used for the thermodynamic reaction, which use precious metals such as platinum. Though durability of stationary fuel cells has also been a major concern in the past, this has improved to meet expectations of any power plant with regular maintenance. Finally, the efficiency of an integrated fuel cell system, which is currently between 40-55% depending on the use [25], is also a barrier for small scale, short duration applications because this efficiency is low compared to other electrical energy storage technologies.. This value is a fundamental result of the electrochemistry in the fuel cell, along with the loss of heat energy. Research is ongoing to improve the efficiency of fuel cell systems by improving the catalyst materials and by making use of the waste heat.

2.3.2. Hydrogen Engines

Hydrogen can also fuel combustion-based power generators such as internal combustion engines and gas turbines. The reaction energy of hydrogen combustion is similar to that of hydrocarbon fuels. Hydrogen internal combustion engine generators are available from a few industrial companies, including Siemens and General Electric. The maximum power output of the currently available systems is around 1 MW. Hydrogen turbine generators can have much larger power capacities, up to 20 or 30 MW. Several large turbine manufacturers, including Siemens, Mitsubishi, and Kawasaki, are in various stages of development and operational testing of hydrogen-powered turbines for electric grid use. The largest project of this kind is currently in construction at the Intermountain Power Project in Utah, where wind energy will be converted to hydrogen to be burned in a modified gas turbine [26].

In a hydrogen turbine power plant, the oxidizer can be air, as in a typical gas turbine, or pure oxygen with the advantage to eliminate NOx emissions. The combustion of hydrogen with pure oxygen requires careful burner design, due to the high temperature and combustion characteristics of this flame option. The Department of Energy (DOE) National Energy Technology Laboratory (NETL) has conducted research on this technology. Several companies are also engaged in development, including Kawasaki Heavy Industries, General Electric and Tascosa Advanced Services. Figure 11 is an example of a hydrogen-oxygen cycle with a bottoming steam power plant. The current status of hydrogen-oxygen turbine development is increasing research and development in both the U.S. and Japan.

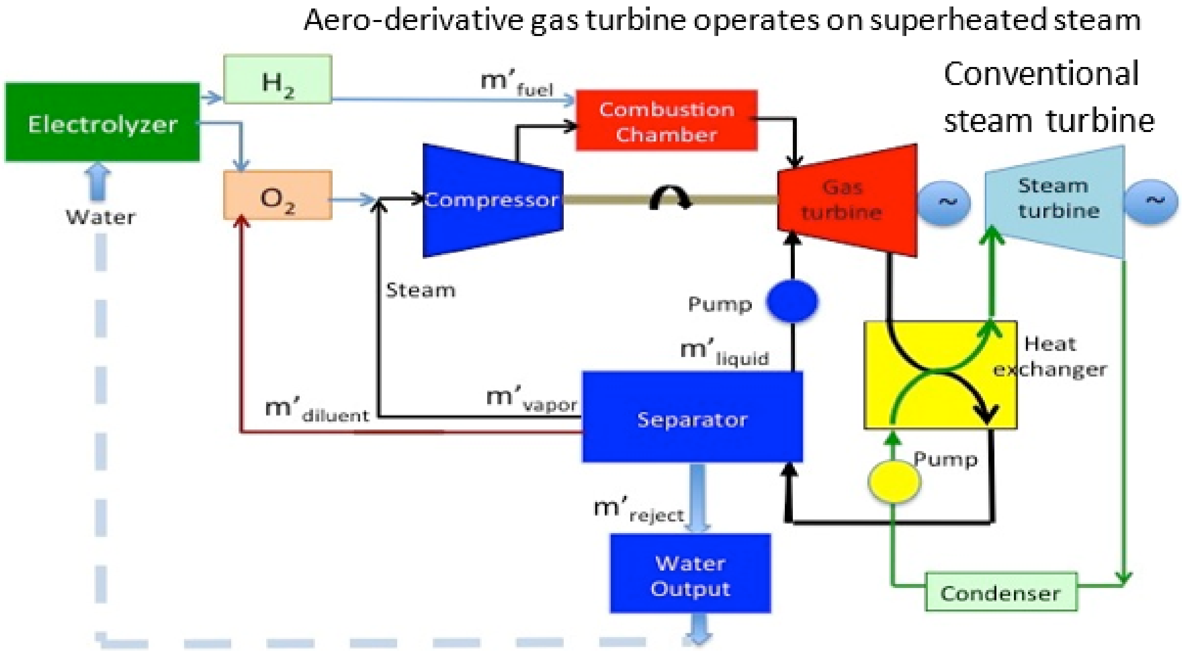

Figure 11. Example hydrogen-oxygen turbine power plant configuration [27]

2.4. Alternative Uses for Hydrogen

Many burgeoning markets for hydrogen that are currently beginning to expand. For instance, hydrogen has unique advantages as a clean fuel for transportation, heating, metallurgical applications, and more. The DOE Hydrogen@Scale program has been evaluating the economic potential of many of these applications [28]. This is significant to the current discussion of hydrogen as a grid asset for two key reasons. Firstly, and most importantly, electrolyzer and fuel cell costs are the major impediment to using hydrogen for storage, and activity in these other markets lead the way to drive down system costs overall as the components are similar regardless of the application.

Secondly, an electric system that incorporates the production of hydrogen would then be able to access additional markets to maximize the revenue from renewable energy production. To recap the earlier discussion, studies suggest that to reach very high renewable penetrations, it will be more cost effective to make more energy than is strictly necessary because this reduces the amount of energy storage that is needed. Though this mode of operation would limit system costs by reducing energy storage requirements, throwing away the excess energy production would represent a significant loss of revenue. Hydrogen production could provide electricity generators a positive outlet for excess electric power by allowing them to generate a valuable product that would provide access to a much wider array of markets and customers.

An overview of several expanding applications of hydrogen outside the electricity market follows.

2.4.1. Transportation

In the area of transportation, fuel cells are already being employed and progress is being made to expand areas of application. Though battery electric vehicles (BEVs) dominate the alternative zero-emission vehicle market, hydrogen powered fuel cell electric vehicles (FCEVs) have some unique advantages over BEVs for end users and grid operators. The most significant advantage for grid operations is that FCEV refueling remains a decoupled process as compared to BEVs which charge directly from the grid. This also has the benefit of reducing unscheduled demands on the grid. Hydrogen can be produced and stored during times of excess generation allowing fueling to occur as needed/desired by end users without further affecting grid operations. A recent study shows that excess energy available in California could contribute a significant fraction of zero-carbon hydrogen fuel for FCEVs in the state [29].

Figure 12: Coradia iLint hydrogen powered train Saxony Germany [30]

The most established, though still small, market is in light-duty vehicles, with multiple car manufacturers (e.g., Toyota, Hyundai, and Honda.) currently producing hydrogen-powered FCEVs. As of 2019, approximately 8,000 FCEVs have been leased or sold in the United States, up from about 150 in 2015 [31].

Furthermore, hydrogen is a preferable on-board storage method to batteries for heavy-duty vehicles and rail applications given the high-energy requirements and hydrogen's relatively low weight [32]. Hydrogen powered buses and trains such as that pictured in Figure 12 are already in use in multiple locations and there is a potential for hydrogen use to expand for these markets, particularly in locations actively transitioning away from fossil fuel transportation, such as Hawaii.

2.4.2. Heating

Heating is another significant energy use sector that is mostly serviced by fossil fuel combustion. In fact, space and water heating accounts for approximately two-thirds of residential energy use and a large percentage of commercial energy use as well. If this sector seeks to decarbonize, even with highly efficient heat pump systems, conversion of all heating loads to electrical formats would present significant transmission and ramping concerns for the grid. Electrical heating loads will exacerbate electric load curve concerns on the grid as heating loads pick up overnight when solar generation goes offline. Conversely, small combined heat and power fuel cell systems such as that pictured in Figure 13 actually produce energy while heating and can help offset spikes in load from electric heaters [33]. This again comes with the further advantage that the necessary fuel can be produced at times that are most beneficial for grid operations as a fully controllable/dispatchable load. Fuel cell heaters are already being employed in some parts of the world, though most of the systems deployed currently use local gas reformation as a source of hydrogen [33].

Figure 13: Home micro-CHP fuel cell systems have taken off in Japan and are expanding into Europe [34]

2.4.3. Fuel Blending

Hydrogen can also be stored or transported by injection into the natural gas grid, in a concept sometimes called "power-to-gas," as illustrated in Figure 14. In some networks, current regulations allow the injection of a fraction of hydrogen into the natural gas grid as a medium to use excess wind or solar energy. Because the energy content of hydrogen gas per unit volume is somewhat less than natural gas, the percent of added hydrogen is generally limited so that the operation of devices designed to work with natural gas, such as stove burners or furnaces, is not adversely affected.

Where it exists, the grid of pipelines for natural gas represents a huge storage vessel that connects to thousands of end users. Even using a small fraction of the natural gas network for hydrogen injections would represent a significant amount of hydrogen storage with little or no additional cost. The resulting gas would then have a reduced carbon footprint, assuming that the injected hydrogen is produced with carbon free methods. However, the hydrogen fuel itself would no longer be carbon-free or pure. While it is possible to separate the hydrogen from the natural gas if a high hydrogen purity is needed for the application, this is an energy intensive process. Regardless, the fuel blending concept represents a low-cost transitional idea to increase the use of hydrogen fuel.

Several fuel blending systems are currently operational in Europe and Canada. An experimental system operates on the campus of University of California–Irvine.

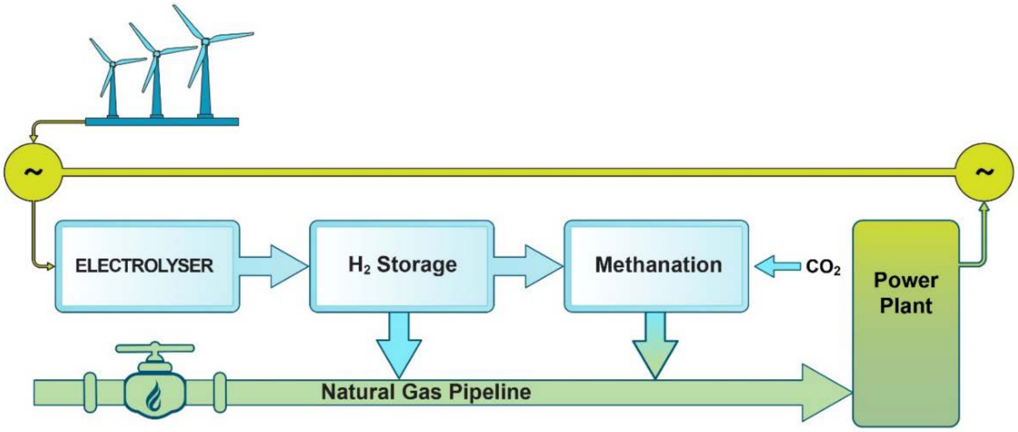

Figure 14. Power-to-gas concepts

One concern with fuel blending is the impact that hydrogen may have on the natural gas pipe network. Hydrogen embrittlement, or cracking of steel pipes exposed to hydrogen, can cause pipes to lose strength and ductility while under stress. Numerous studies have shown minimal effects if the hydrogen is kept to low concentrations, under about 10% [35]. Alternatively, hydrogen can be converted to methane in a methanation reaction with waste or by-product carbon dioxide and then used in any normal application of natural gas. This methane is sometimes called synthetic natural gas or substitute natural gas. Various methanation processes, both chemical and biological, for producing synthetic natural gas are in development worldwide [36].

The exothermic reaction of hydrogen with CO_2 in an industrial setting typically takes place on a metal catalyst.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad -164\,\text{kJ/mol} \tag{4}$$

The similar biological reaction uses a bio-catalytic (microbial) processes in an aqueous reactor or fermenter under anaerobic conditions.

3. Safety Considerations

One of the concerns with any hydrogen system is safety. Though hydrogen is a dangerous material, the safety concerns are essentially no different than those associated with the storage of any flammable gas, such as propane or natural gas. In fact, a number of industries have been producing, storing, and transporting hydrogen safely for decades. There are some hydrogen specific considerations though, and if the use of hydrogen expands with new technologies to store, transport, and use hydrogen, safety standards will need to be kept current to ensure safe handling.

3.1. Pressure

As discussed in Section 2.2, gaseous hydrogen is stored at high pressure, typically 350 bar (5,000 psi) or 700 bar (10,000 psi) to improve the energy density of the storage systems. Storage of any material at such high pressures is a safety risk that requires proper system design to overcome.

Paramount among mitigation strategies are those typical for storage of gases of any kind at these pressures, such as proper selection and placement of the pressure relief valve to avoid any major failures.

3.2. Fire Safety

Fire safety is always a concern whenever flammable gases are being handled, and hydrogen does have some key characteristics that require special consideration relative to other gases. The flammability limits of flammable gases are defined as the minimum and maximum concentrations of the gas in a gas/oxidizer (e.g., air) mixture that will lead to flame propagation if the mixture is ignited. Hydrogen has a wider range of flammable concentrations (4% to 74%, as shown in Table 2) as compared to other gases. For instance, the flammable range of propane is approximately 2% to 10%, and methane is flammable at concentrations of 5% to 15% [37]. The wider flammability range is often cited as a point of concern for hydrogen systems, but the lower flammability limit of hydrogen, which is the design limit for fire safety systems, is comparable to that of other flammable gases. With proper ventilation, enough air can be entrained in the space to keep concentrations below the lower flammability limit and mitigate ignition concerns.

Table 2. Flame characteristics of common combustible gases [37]

Property	Hydrogen	Methane	Propane	Gasoline Vapor
Upper Flammability Limit in Air [%]	74	15	10.1	7.6
Lower Flammability Limit in Air [%]	4.1	5.3	2.1	1.4
Most Easily Ignited Mixture in Air [%]	29	9	4	2
Adiabatic Flame Temperature [°F]	4,010	3,562	3,573	3,591
Buoyancy [Fuel Density—Air Density Ratio]	0.07	0.55	1.52	4
Minimum Ignition Energy (MIE) [mJ]	0.02	0.29	0.48	0.2
Autoignition Temperature [°F]	1,085	1,003	914	450

For hydrogen systems, leak detection devices should be placed toward the top of enclosed spaces or ventilation systems because hydrogen is buoyant in air, unlike heavier gases such as propane or gasoline vapor [37]. In outdoor systems, the high buoyancy of hydrogen reduces the associated hazards because any gas released disperses very quickly, lowering the chances of local buildup and reaching the lower flammability limit. Another important consideration is the amount of energy needed to ignite a hydrogen gas mixture or the minimum ignition energy (MIE). At the most ignitable concentration of hydrogen (29% hydrogen in air), very little ignition energy is needed, and a simple static discharge can light the mixture. However, at concentrations near the lower flammability limit, the MIE is comparable to that of other fuels. In cases where a hydrogen leak is ignited, the high dispersion rate and buoyancy leads to quick dissipation unlike with heavier gases that can remain concentrated leading to more concentrated damage. All of this is to say that though there are fire hazards associated with hydrogen, they are ultimately no more severe than those for other flammable gases. However, some unique considerations and fire safety plans should be approached with a hydrogen-specific focus.

3.3. Liquid Hydrogen Safety

Liquefied hydrogen is stored at cold temperatures (20 K or -253 °C) and generally moderate pressures (less than 150 psi) [37]. The low storage temperature necessitates the use of boil-off ventilation systems specifically designed for hydrogen. Oxygen and nitrogen in the air can condense and solidify in the presence of cold hydrogen gases, which can foul venting systems that are not specifically designed to handle this issue. Liquefied oxygen from venting or liquid hydrogen transfer lines can be a fire hazard as localized areas with very high oxygen concentrations and therefore potentially flammable can form while the liquid evaporates. Setback distances from occupied buildings for liquid hydrogen systems should be carefully considered.

4. Concluding Remarks

Hydrogen is a unique storage medium that could be used both as a suitable long-duration storage option and valuable use of energy that would otherwise need to be wasted for grid operations. Though the power components of a hydrogen energy storage system are more expensive than those of most other energy storage technologies, it is relatively inexpensive to store large amounts of energy as hydrogen or in a hydrogen carrier material. Hydrogen is generally not practical for small quantities of energy storage but is cheaper than batteries for storage durations above about 12 hours, despite the lower roundtrip efficiency and cost of electrolyzers/fuel cells. For storage needs of days, weeks, or months in grid applications, energy storage in the form of hydrogen would be much cheaper than most other options because of the low cost of gas storage.

Research and development to improve performance and lower costs of hydrogen system components is being undertaken by both government research agencies and industry worldwide. The U.S. DOE had just released a Hydrogen Program Plan similar to those of many other countries and industry groups such as the Hydrogen Council. While the research emphasis is on performance (efficiency and reliability) and cost at the materials level, industry efforts are focused on scale up of manufacturing to further reduce costs. For integrated systems such as grid energy storage, efforts are focused on policies to make use of curtailed renewable energy and demand response markets.

Predictions of future high renewable penetration grids suggest that the least-cost network configurations will waste a significant amount of renewable energy to minimize the energy storage requirements. In this case, hydrogen becomes an attractive energy use for excess renewable power because it can be applied to a wide array of markets outside of the electric grid and can be produced on a schedule that most benefits the electric system. Electricity generators could use hydrogen to expand their customer base and take advantage of energy they produce that would otherwise be wasted. Long-term planning, particularly if a significant expansion of renewable generation is the goal, should consider hydrogen energy storage as a potential solution.

As a final note, safety is always a concern whenever hydrogen is mentioned. Hydrogen is a flammable gas that needs to be handled with care, but it is generally no more dangerous than any other flammable gas stored at high pressure despite the common misconceptions. Hydrogen can be ignited more easily than other gases in some cases, but also disperses quickly in the event of a leak. In fact, in thoroughly ventilated cases, such as outdoors, it is generally considered to be less hazardous than many other gases. There is already an established network of hydrogen production, storage, and use for multiple industries that has been operating safely for decades. Systems need to be safely designed for the properties of hydrogen, but this should not stop planners from taking advantage of this uniquely flexible and scalable energy storage medium.

Dr. Alexander Headley is currently a postdoctoral appointee in the Energy Storage Technology and Systems department at Sandia National Laboratories. His current research is focused on evaluating the potential of energy storage systems for grid support, integrated system design, and the development of demonstration facilities for grid-connected energy storage. Given his background in Thermal/Fluid Systems, Dr. Headley is also developing thermal models of grid-scale lithium ion battery systems for control and design support. Before joining Sandia, Dr. Headley earned his master's and PhD in mechanical engineering at The University of Texas at Austin.

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