What's All the Buzz About Hydrogen!

Standards and Deployment

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Anyone who is following climate change issues and the expansion of the use of renewable energy would have seen the subject hydrogen popping up all over the place. Just do a Google search using the following words "*hydrogen renewable energy climate change*" and dozens of links will be displayed promoting the use of green or renewable hydrogen, made from the electrolysis of water powered by solar or wind, as indispensable in achieving climate neutrality.

According to the U.S. Department of Energy (2020), hydrogen energy storage (HES) offers unique benefits beyond the potential for long-term, seasonal energy storage as stated in the Energy Storage Grand Challenge Roadmap. Examples include grid leveling and stabilization services and coupling with intermittent renewable energy sources to enable reliable, emission-free electricity. Figure 1 is a graphic highlighting how hydrogen can play a central role in both bidirectional and one-way energy storage.

A RECENT NEWS STORY REPORTED:

Hydrogen initiatives are accelerating globally.

200+ large-scale projects have been announced across the value chain, with a total value exceeding $300 billion

30+ countries have national hydrogen strategies in place, and public funding is growing

Traditionally, hydrogen is produced in a steam-methane reforming process where methane reacts with steam under 45-375 psi (3-25 bar) pressure in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Hydrogen produced in this manner is often referred to as '**gray hydrogen**' since it relies on the use of a fossil fuel and produces carbon dioxide as a byproduct. But with the expansion of low-cost renewable energy, the majority of the large hydrogen production projects underway around the world are making hydrogen via electrolysis. Hydrogen produced in this manner is referred to as '**green hydrogen**'.

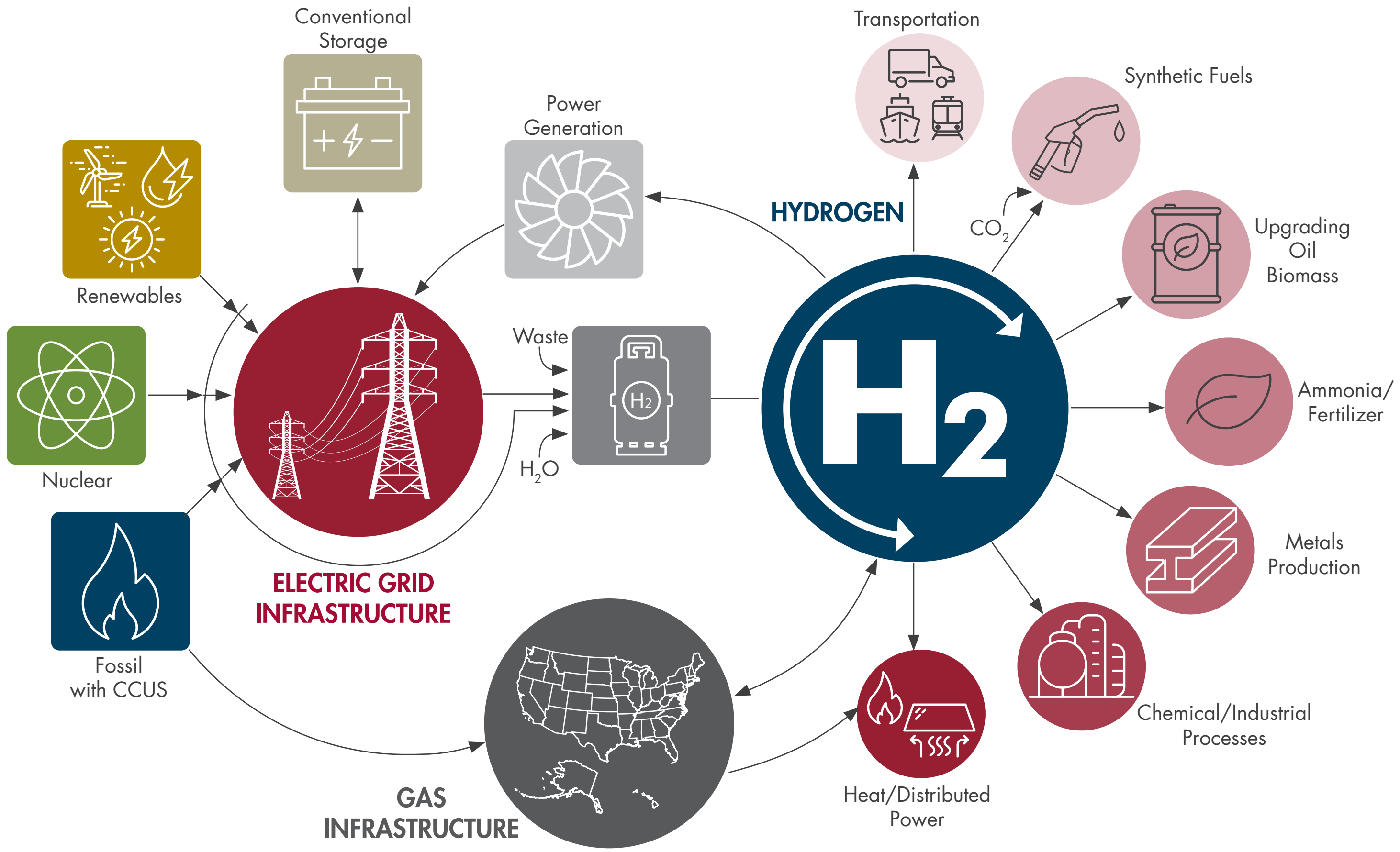

FIGURE 1. The H2@Scale vision: hydrogen can play a cenral role in both bidirectional and one-way energy storage[145]
Ref: DOE Energy Storage Grand Challenge Roadmap

Here is a short list of hydrogen projects underway around the world as reported in the news:

1. HyDeal Ambition (67GW)
   - Location: Multiple sites across Western Europe, starting in Spain in southwest France, and then extending to eastern France and Germany.
   - H2 output: 3.6 million tonnes per year
2. Asian Renewable Energy Hub (15GW)
   - Location: Pilbara, Western Australia
   - Planned use of H2: Green hydrogen and green ammonia for export to Asia.
3. AquaVentus (10GW)
   - Location: Heligoland, Germany
   - Power Source: Offshore Wind
   - H2 output: one million tonnes per year
4. Helios Green Fuels Project (4GW)
   - Location: Neom, a planned city in the northwest Saudi Arabia
   - Power source: Onshore wind and solar
   - Planned Use of Hydrogen: to produce green ammonia, which would be transported around the world and converted back into H2 for use as a transport fuel.

On a mass basis, hydrogen has nearly three times the energy content of gasoline [120 MJ/kg for hydrogen versus 44 MJ/kg for gasoline]. But there are challenges storing and transporting hydrogen. The low volumetric density of hydrogen makes it quite expensive to store and transport it in gas or liquid forms. [To exist as a liquid, H2 must be cooled below its critical point of 33K (-240°C, -400°F)] Alternatively, to store hydrogen as a gas economically, it typically needs to be compressed between 350-700 bar (5,000 - 10,000 psi). Either of these methods is energy intensive and costly. One option that has also received a lot of attention is converting hydrogen to ammonia using a process called the Haber-Bosch process.

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Ammonia has several desirable characteristics that suggest its use as a medium to store hydrogen. It can be liquefied under mild conditions (Thomas and Parks, 2006). The vapor pressure of ammonia at room temperature is 9.2 bar (121 psi G). Its physical properties are similar to those of propane, meaning that it can be stored in a simple, inexpensive pressure vessel. Ammonia also has a large weight fraction of hydrogen; hydrogen makes up approximately 17.6% of the mass of ammonia. When these two factors are combined, the result is a liquid that is simply contained, with a volumetric hydrogen density about 45% higher than that of liquid hydrogen. This is why many companies are looking at the option of producing hydrogen using excess renewable energy and then converting it to ammonia. The ammonia is then transported around the world, where at its final destination would once again be converted back to hydrogen for use in power generation, transportation, and even residential cooking and heating.

Based on the information presented above, it comes as no surprise that HSB and SIA have been receiving numerous inquiries about constructing pressure vessels for production and storage of hydrogen and ammonia. Some of you may be old enough to remember the talk about the developing hydrogen economy in the early 2000's. During that timeframe ASME committees carried out much work to develop rules within its standards for the generation, storage, and transport of hydrogen. Today rules exist for the construction of pressure vessels and piping within Section VIII and B31.12 to be used in the production and transport of hydrogen. Let's take a closer look at the rules within the ASME standards, and some of the manufacturing challenges.

ASME Standards and Hydrogen

Infrastructure equipment made to store and handle hydrogen during its production, distribution and use is critical to the successful implementation of hydrogen as an energy storage medium. ASME has had standards used in the design and manufacture of hydrogen vessels for many years. In recent years, ASME has focused on standards related to the hydrogen.

There are many different designs used in the construction of vessels for hydrogen storage and transportation. A common design uses ASME Section VIII, Divisions 2 and 3 (VIII-2 & VIII-3) for a seamless pipe with the ends hot formed to a hemispherical dome on each end made of low alloys steels. Similar cylinders have a composite wrapped steel liner leveraging VIII-3 and Section X as Composite Reinforced Pressure Vessels (CRPV's). There are also ASME Section X cylinders which are composites with stainless-steel end bosses for connections on each end.

ASME Section VIII, Division 1 (VIII-1) is the most used standard for the design and construction of pressure vessels around the world. The scope of VIII-1 is for vessels with pressures generally not exceeding 3000 psi (20 MPa) and is common for low pressure storage vessels. VIII-1 has the largest design margin (3.5) and typically uses lower strength steels, known for higher ductility. ASME developed VIII-2 in the late 1960's. Today, it has two classes of vessels with a design margin of 3.0 and 2.4. ASME VIII-3 has been published since 1997 and is generally for pressure vessels over 10 ksi (70 MPa) with the lowest design margin of 1.8.

Many applications in the hydrogen economy, however, are requiring higher pressures to make transport of the gas more economical (Office of Energy Efficiency & Renewable Energy, 2016). Due to its low energy volume, most cars are operating with a high-pressure tank (vessel) of 10,000 psi (69 MPa) containing 5 kg of compressed hydrogen. These cars are typically filled at stations with storage vessels that are 15,000 psi (103 MPa).

ASME VIII-2 has many higher strength materials allowing lighter weight and more economical vessels. However, fatigue becomes a more prevalent issue due to the higher stresses. Evaluation of the life of the vessels in key critical areas and establishment of an in-service inspection program is critical to long term safe operation. VIII-2 includes a fatigue assessment methodology for most materials permitted for construction but leaves addressing the hydrogen environment up to the designer.

ASME acknowledges that it does not cover many cases of environmental

effects such as hydrogen. ASME Section II-D, Nonmandatory Appendix A A-702 contains general information regarding hydrogen damage, embrittlement, blistering, and cracking. However, little specific guidance is provided to the designers of hydrogen equipment.

ASME formed a special "Project Team on Hydrogen Tanks" to develop rules for design in hydrogen environments in the early 2000's. The committee consisted of industry representatives and worldwide researchers involved in high-pressure hydrogen infrastructure. The rules first appeared in 2007 in ASME VIII-3 in KD-10 "Special Design Requirements for Vessels in High Pressure Gaseous Hydrogen Transport and Storage Service".

KD-10 captured the industry experience along with recommendations for testing for hydrogen service. This included criteria such as the relevance of the hydrogen partial pressure of hydrogen 6,000 psi (seamless) and 2,500 psi (welded). KD-10 mandated evaluation of fatigue cracking using fracture mechanics and required Manufacturer's to test materials for fatigue crack growth rate (da/dN) and the threshold for hydrogen assisted cracking (KIH). Fatigue crack growth rate and KIH testing has since been completed by laboratories worldwide, including Sandia National Lab, Savanah River National Lab, NIST, and Japan Steel Works on two common industry materials (SA-372 and SA-723) used for storage vessel construction. Code Case 2938 was first published in early 2019 to eliminate the need for Manufacturers to perform redundant testing to comply with KD-10. This testing showed significant increase in crack growth rate and limitations of critical crack size compared to the materials used in an inert environment.

Other standards for supporting hydrogen storage tanks include ASME Section X that contains requirements for fiber-reinforced thermosetting plastic pressure vessels. This standard is used both for cylinders of fully composite materials and the CRPV's which are manufactured to VIII-3 and ASME Section X Appendix 8 (Class III).

Hydrogen storage also relies on piping and piping components for connection of the vessels to storage vehicles, etc. ASME B31.12 (2008) responded to the need for piping and piping components in the hydrogen market. This standard references other B31 standards to incorporate "best practices", such as B31.3, Process Piping; B31.1,Power Piping; B31.8, Gas Transmission and Distribution Piping Systems; B31.8S, Managing System Integrity of Gas Pipelines; and VIII-3.

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An additional challenge for many operators will be the life management. The fracture mechanics design approach of ASME VIII-3 or even the fatigue based approach of an ASME VIII-2 vessel will result in a vessel with a finite life. Some equipment was installed less than ten years ago is already exceeding the design life. Requalification of vessels in fatigue service is not new. ASME PCC-3, Inspection Planning Using Risk Based Methods, contains methodology for requalifying vessels in cyclic service that has been in use for decades. The method allows for continued use of the vessels beyond the design basis with a proper program of asset management, maintenance of the design basis documents, tracking of in-service cyclic usage, and periodic inspection for plausible failure modes. And of course, consideration of jurisdictional requirements should not be overlooked.

Unfortunately for many end-users, it is not uncommon to develop an in-service inspection program to be considered during design or installation. Even simple seamless cylinders are often mounted in racks making disassembly of the system necessary to access even the OD of the cylinders.

Methods for evaluation of many of the hydrogen damage modes, if found, are contained in API 579-1 / ASME FFS-1, Fitness for Service Standard. Many of these damage assessment procedures can be implemented, including evaluation of the continued life of the vessel using fracture mechanics. However, consideration of the effects of hydrogen embrittlement from KD-10 and Code Case 2938 should be considered.

There have been several case studies recently regarding the use of the methods in the ASME standards for life assessment in hydrogen environments, particularly with Code Case 2938. Discussions at the ASME Pressure Vessels and Piping (PVP) conference, as well as with the study group has led to additional study about lower pressure hydrogen and the effect on fatigue life. This will be published at the upcoming ASME PVP 2021 Conference and will show that even at pressures as low as 1 bar of hydrogen, there can be substantial detrimental effect on the life of hydrogen equipment (Ronevich and San Marchi, 2021). This could have significant future ramifications in all parts of ASME's hydrogen codes and standards, including ASME VIII-1 or other low pressure vessels.

SUMMARY

The need to dramatically reduce CO_2 emissions and meet global warming goals will drive market changes that will impact all our lives for decades to come. In the last 10 years, there has been exponential growth in renewable energy in the form of solar and wind, with decreasing costs as mass production efficiencies are achieved. Many countries are betting on hydrogen to be one of the key components in achieving our environmental goals. This will drive the demand for pressure equipment to be used in the production, storage, and transmission of energy storage media such as hydrogen and ammonia.

ASME continues to evolve and advance its standards to keep pace with technology and the research supporting it. Many industries have gone through similar evolutions to ensure that the equipment and personnel using it are able to function safely and design for the unknowns. A key aspect of the long-term success of the hydrogen economy will be not only in design, but in successful safe operation of the equipment over time in a cost effective manner. ASME will continue to develop standards for supporting the entire life-cycle of hydrogen equipment.

Footnotes

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