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Hydrogen Storage

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Intelligence Report

CONTENT

1. INTRODUCTION TO H AND H2

Hydrogen is a chemical element with the symbol H and atomic number 1. It is the simplest, lightest and most abundant element in the universe. Yet, in nature, hydrogen does not typically exist by itself. It has to be produced from compounds that contain it – one of them being water (H_2O).

Figure 1: Hydrogen in the periodic table. Author: Science Activism. License: Creative Commons, Attribution 2.0 Generic (CC BY 2.0).

The most common form of hydrogen is hydrogen gas with the molecular formula H_2, consisting of two protons and two electrons.
At normal temperature and pressure, hydrogen is a gas, but it condenses to a liquid at -423 degrees Fahrenheit or -253 degrees Celsius.
At present, there are a number of ways to produce hydrogen, each given a colour to distinguish it easy.

GREY: Before the latest technological advancements, grey hydrogen was the industry standard. It is produced from natural gas in a process known as steam methane reforming (SMR), which releases carbon emissions into the atmosphere.

BLUE: Blue hydrogen is produced in the same way, but the process relies on carbon capture and storage (CCS) to mitigate the environmental impact to some extent.

GREEN: Then there is green hydrogen. It is produced in a process called electrolysis where an electrolyser is used to break down water into hydrogen and oxygen (O_2) with no carbon emissions whatsoever. Electrolysers can run solely on electricity from renewable sources such as wind, solar, hydro and biomass, or even solid waste. When solar energy is used, the output can be sometimes labelled as yellow.

PINK: Pink hydrogen is also produced with electrolysis but the low-carbon energy source is nuclear energy power.

TURQUOISE: The production of turquoise hydrogen, on the other hand, requires a separate process known as pyrolysis of methane (CH4) in which methane is split into solid carbon and hydrogen in a reactor.

Over the past couple of years, green hydrogen has attracted significant interest as a future pillar of the energy transition in its capacity as an energy carrier. It will play an important part in the decarbonisation of transport and industry, while also providing a new way to store renewable power. Storing hydrogen is in itself a process that brings a number of challenges. There are a number of methods to store it as gas or liquid, while a lot of research is taking place with the goal of increasing safety or lowering costs.

2. METHODS OF STORING H2

Hydrogen is the lightest gas in the universe, with 1 litre weighting just about 90 mg under normal atmospheric pressure, so it occupies a substantial volume when stored under standard conditions. Specifically, about 11 cubic metres is required to store a kilogram of hydrogen – the quantity you would need to drive 100 km. This volume can fill the trunk of a large utility or commercial vehicle. Depending on the use case, today there are a few different methods of storing hydrogen, divided between physical and material-based options.

Physical-based

Physically, hydrogen can be stored either as a gas, which typically requires high-pressure tanks, or as a liquid at cryogenic temperatures. The two techniques can be combined as well. Physical storage is currently the most mature technology.

Pressure vessels for gas

Usually, hydrogen gas is compressed to pressure values of between 100 bars and 825 bars for large-scale storage. The gas could be stored in pressure vessels ranging from small bottles to huge storage tanks.

Apart from their size and capacity, the vessels differ in terms of the materials they are made of. Some use metals like carbon steel and low alloy steel, while others consist of a metal liner with varying thickness or a polymer liner. There is also an innovative but costly option involving a linerless fully composite pressure vessel that is based on a fiber-reinforced shell.

Liquefaction

Storing hydrogen as a liquid is the option of choice when the required hydrogen volume has to be reduced further than compression allows. However, getting to the liquid form requires 64% more energy than what is needed for high-pressure hydrogen gas compression because of the cryogenic temperatures required by the process.

The actual storage of the liquid takes place in insulated tanks that can maintain low temperatures and minimise evaporation.

Due to its complexity, this technique has historically been viewed as very costly.

Geological storage

Apart from tanks, hydrogen gas can also be stored underground in large salt caverns. Depleted natural gas or oil reservoirs, as well as aquifers, are also considered to be good options for the large-scale and long-term storage of hydrogen. These are all referred to as geological storage.

Salt caverns are typically built near larger hydrogen production sites and electrolysers. The method is not new because similar facilities have already been used for natural gas storage.

Linde Plc, which has been operating the world's first commercial hydrogen high-purity cavern for more than a decade now, explains that the hydrogen gas has to be purified and compressed before it can be injected into the cavern.

The process of creating the cavern includes drilling into the salt and then injecting water to dissolve the salt. The resulting mixture – brine – is extracted, leaving a large room where the hydrogen can be stored under pressure.

While the underground storage of hydrogen is considered safe, flexible and resilient, it comes with its own challenges, including the relative scarcity of salt deposits around the world and a possible impact on the purity of the stored hydrogen.

A Scottish startup called Gravitricity is looking into the possibility of combining underground gravity-based storage with hydrogen and inter-seasonal heat storage. The firm is investigating opportunities for purpose-built prototype shafts at brownfield locations in the UK.

Material-based

Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption). This method allows for the storage of larger quantities of hydrogen in smaller volumes. Also, it is being done at low pressure and at temperatures that are closer to room temperature.

Physisorption and chemisorption

When it comes to solid-state systems, there are two different methods for hydrogen storage -- physisorption and chemisorption. In physisorption, H2 molecules are adsorbed on the surface of an adsorbent because of the intermolecular force that exists between hydrogen and the storage medium (the adsorbent). Examples of such materials are carbon nanotubes, activated carbon, zeolites and metal-organic frameworks (MOFs). They have good reversibility and relatively fast kinetics, but suffer from low hydrogen storage and require low temperatures for larger hydrogen storage capacities.

In chemisorption, hydrogen chemically reacts with solids, which results in the production of metal, complex and chemical hydrides. These are characterised by high hydrogen density but their hydrogenation and dehydrogenation are very complex and their reversibility is relatively low. The processes also result in energy efficiency reduction.

Methanol & Ammonia

While this is not the most environmentally-friendly solution, methanol (CH3OH) can also be used for hydrogen storage. This method leads to the release of carbon dioxide (CO2) when methanol is directly utilised or decomposed, and the separation is also an energy intensive process.

Contrastingly, ammonia is viewed much more favourably as a storage option due to its high hydrogen density and the fact that it could be utilised in both mobile and stationary applications. It can be used directly as fuel but, if needed, the stored hydrogen can be extracted too. Another advantage is that the production, storage and transportation infrastructure for ammonia is already established globally.

Ammonia offers a way to more easily turn hydrogen into a liquid fuel compared to using liquefaction. It can be produced from both fossil fuels and renewable energy sources through a number of processes, including pre-treatment, conversion and synthesis. As a bonus, surplus power can be converted to hydrogen, which is subsequently converted to ammonia, too.

Picture 1: The Yara Pilbara ammonia plant in Western Australia. Source: Yara Australia Pty. Ltd.

3. CHALLENGES

Each of these methodologies has its own advantages and disadvantages, which makes them suitable for different applications. The hurdle of too high a cost, though, is present in each case, and there are technical challenges as well. In any case, storing large quantities of hydrogen over an extended period of time is a critical issue.

For road transportation, the biggest challenge lies in storing enough hydrogen in a durable system with limited weight and capacity and at the same time supporting the conventional driving range of more than 300 miles in a light-duty vehicle. Two additional issues in transportation targeted by the US Hydrogen and Fuel Cell Technologies Office (HFTO) are refueling times and cost.

The office estimates that current refueling times are too long and need to be reduced to less than three minutes. It also points at the need to develop low-cost materials and components for hydrogen storage systems, as well as low-cost, high-volume manufacturing methods in order to lower the cost of on-board hydrogen storage system, which, presently, is too high.

In its 2021 Annual Merit Review and Peer Evaluation Report, the HFTO mentions that a key milestone under the Hydrogen Technologies subprogramme is to develop onboard hydrogen storage systems for Class 8 long-haul tractor-trailers, achieving a cost of USD 9/kWh by 2030 and the capability to withstand 11,000 pressure cycles.

The HFTO notes that research, development and demonstration (RD&D) activities when it comes to physical storage methods (Near- to Mid-Term High-Pressure Tanks and Other Physical Hydrogen Storage Options) are focused mainly on cutting cost and minimising losses from tanks and other currently available technologies for compressed gaseous and liquid hydrogen storage.

When it comes to the long-duration storage of hydrogen gas in bulk in underground rock-lined or salt caverns, the big disadvantage of this approach is that it is limited to specific geographical areas. The office also points out that further research and optimisation are needed to address cost and safety issues.

Another topic to be discussed when considering the storage of hydrogen in caverns is the composition and purity of the hydrogen. There is the possibility of bacteriological and chemical reactions taking place in the cavern, resulting in the modification of the overall composition of the gas. Purification could then be required. This is all the more valid if hydrogen is planned to be stored in depleted natural gas or oil reservoirs.

On the other hand, hydrogen loss could be an issue for aquifers because of reactions with rocks, fluids and microorganisms.

The table below can help compare key advantages and disadvantages of select storage options.

Type	Advantages	Disadvantages
Gaseous tank storage	Most mature technology	Offers only low storage densities, safety concerns due to high pressures and flammable nature
Cryogenic liquid storage	Higher storage density	Very energy-consuming, supports only short-term storage due to transfer and evaporation losses
Ammonia	High volumetric density, stable for long-term storage, can make use of existing infrastructure	Toxicity
Metallic hydrides storage	Supports long-term storage, feasible at pressures below 30 bar	Very low thermal conductivity
Liquid hydrogen carrier storage	Large-scale option	Currently used only in demo projects

The most important factor for hydrogen vessels is storage density. The higher it goes, the more economically feasible the system gets.

Density is measured as the amount of mass contained per unit volume. Hydrogen has very low density both as a gas and a liquid, and because of that its storage requires large vessels made of costly materials and high cost of maintenance. As one would expect, it is more expensive to store hydrogen at higher pressures than at lower.

The figure below compares the gravimetric density of some of the storage medium (wt.-%, reflects the capacity of a medium to integrate a part of hydrogen).

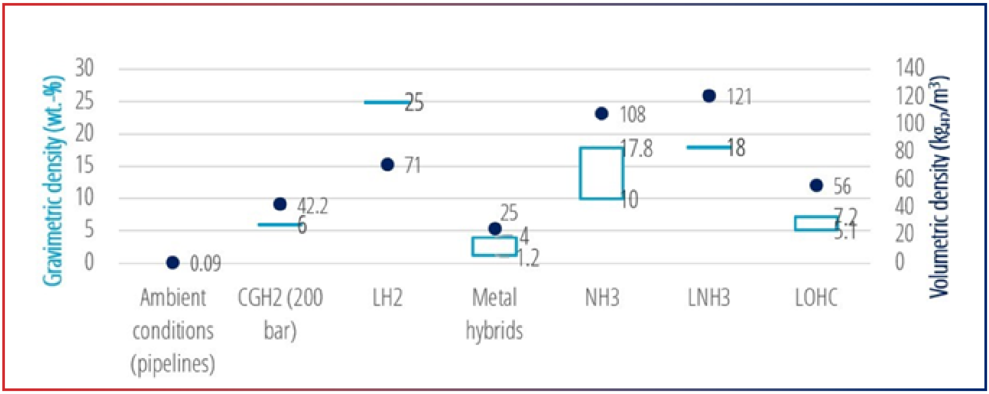

Figure 2: Hydrogen storage medium capacity. Source: Compilation of data and research from Enerdata. CGH2 = compressed hydrogen; LH2 = liquid hydrogen; NH3 = ammonia; LNH3 = liquid ammonia; LOHC =liquid organic hydrogen carriers;

4. CASE STUDIES

In this section of the report you will find a few examples of hydrogen storage projects on a large scale. They are not necessarily the largest of their kind and were selected to represent different geographical markets.

Advanced Clean Energy Storage Project (USA)

In May 2019, Mitsubishi Hitachi Power Systems (MHPS) and Magnum Development announced the Advanced Clean Energy Storage (ACES) project in the US state of Utah, as part of which they plan to develop a gigawatt-scale project involving four types of clean energy storage. The featured technologies include: renewable hydrogen; compressed air energy storage; large-scale flow batteries; and solid oxide fuel cells.

Magnum Development says it is the owner of the only known “Gulf Coast” style domal-quality salt formation in the Western US. The salt dome in question encompasses about 4,810 acres adjacent to the Intermountain Power Plant (IPP) near Delta and is large enough to support over 70 caverns, each storing up to 5,500 metric tonnes of hydrogen.

“Magnum’s site adjacent to the Intermountain Power Project is positioned to take full advantage of existing regional electricity grid connections, fully developed transportation infrastructure, ample solar and wind development capacity, a skilled workforce currently transitioning away from coal, and, of course, the unique salt dome opportunity,” Craig Broussard, CEO of Magnum, commented at the time.

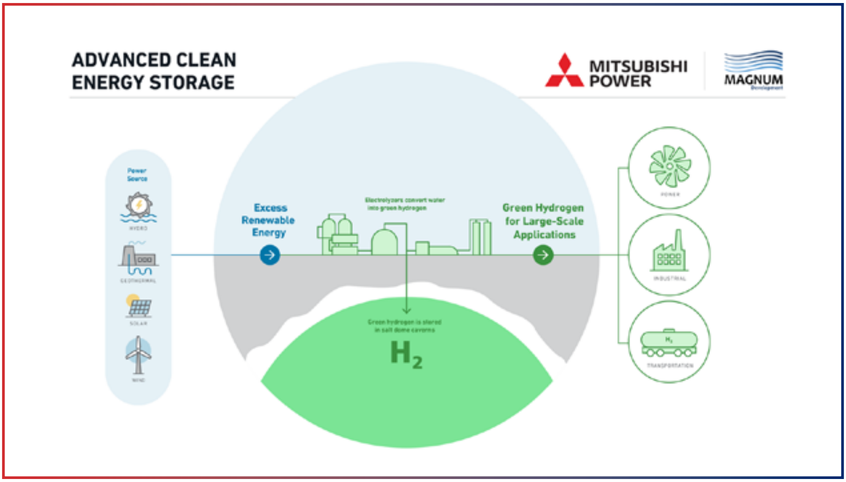

Figure 3: The ACES scheme. Source: Mitsubishi Power Americas, Inc.

According to information included in the Environmental Assessment (EA), the scheme is to be realised in two phases in the period 2022-2026. Phase I will include the installation of 220 MW of electrolysers, two storage caverns, two brine evaporation ponds and associated ancillary support facilities. Construction of that phase is expected to start in 2022, with completion of the first 220 MW of hydrogen production capacity and one storage cavern targeted for 2024.

Phase 2 envisages deploying 330 MW of electrolysers, two additional storage caverns and associated ancillary support facilities. It is seen to enter construction in 2025 and be finalised as early as 2026.

To fund ACES's construction and initial operation, the developers have applied for financial assistance under a loan programme of the US Department of Energy (DOE). The Loan Programs Office (LPO) has reviewed and determined that the application is substantially complete. It has now been entered into LPO's due diligence process.

The ACES project has the backing of Haddington Ventures LLC.

Aldbrough Hydrogen Storage project (UK)

In 2021, SSE Thermal and Equinor announced they were developing a large-scale low-carbon hydrogen storage facility at their co-owned Aldbrough Gas Storage site on the East Yorkshire coast. The existing site comprises nine underground salt caverns.

The partners pointed out that in order to implement the project, they will need to either convert the existing caverns or create new purpose-built ones. The storage capacity of the resulting facility is initially expected to be at least 320 GWh, which is enough to power over 860 hydrogen buses for a year.

At first, the Aldbrough site is planned to store blue hydrogen produced for the Keadby Hydrogen Power Station, proposed by SSE Thermal and Equinor as the world's first 100% hydrogen-fired power station. The duo, though, notes that the project has the potential for green hydrogen storage as well.

In January 2022, the partners said they had awarded major contracts to engineering firm Atkins and sustainability consultancy Environmental Resources Management (ERM). Atkins will carry out a feasibility study to assess the design of the caverns as well as the corresponding pipeline to transport hydrogen to and from the proposed new Humber Low Carbon Pipelines (HLPC). SSE Thermal and Equinor said that the outcome of the assessment will provide the foundation for the next phase of scoping work as the project matures.

The Aldbrough Gas Storage facility could become operational by early 2028.

HyPSTER demonstrator (France)

The HyPSTER project is the first EU-supported, large-scale green hydrogen underground storage demonstrator. The name stands for Hydrogen Pilot Storage for large Ecosystem Replication.

Picture 2: The site of the HyPSTER project in Etrez, France. Source: HyPSTER.

With a budget of EUR 13 million, this pilot project was launched in January 2021 with the goal of demonstrating the use of salt cavern storage to connect hydrogen injection by electrolysis to industrial and mobility uses. It will also test the technical and economic reproductibility of the process to other European sites.

HyPSTER is a collaborative effort between ESK GmbH, Armines-Ecole Polytechnique, Ineris, Axelera, Element Energy, Storengy and Inovyn. Storengy, an underground natural gas storage specialist and a unit of France's Engie, is the project coordinator for all partners.

The project takes place at a Storengy underground gas storage site at Etrez in eastern France. It envisages the use of a 1-MW electrolyser for the production of green hydrogen that will be subsequently stored in the salt cavern. The particular cavern has a potential storage capacity of 44 tonnes of hydrogen. Between 2 and 3 tonnes of hydrogen will be stored during the first stage of the project. In January 2022, it was announced that the project was proceeding with the finalisation and validation of the engineering studies that would enable the construction phase to start. At the time, the project participants had already contracted the equipment required for the surface and underground works. Elogen was contracted to supply the PEM electrolyser for the facility, Howden was chosen to provide a compressor for the production platform and dispensing solutions, Schlumberger was in charge of completion elements, while TechnipFMC was selected to participate in the development of a hydrogen wellhead. In addition, Schneider Electric will contribute its expertise in electricity, instrumentation and automation solutions.

Storengy plans to begin construction of the platform in the first half of 2022. The salt cavern will then need to be converted because up until now it has been used for R&D projects for natural gas underground storage. Hydrogen production is to be initiated in March 2023 with an experimentation phase in real conditions.

The project stakeholders say that HyPSTER will support the French regional hydrogen strategy by making possible the development of a local hydrogen hub. HyPSTER is also expected to pave the way towards replication with the target to go below a hydrogen storage cost of EUR 1 per kg for the potential 40 TWh of salt cavern storage sites in Europe.

The project is backed by the Clean Hydrogen Partnership – the successor of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

HyCAVmobil research project (Germany)

German energy, telecommunications and IT group EWE owns 37 salt caverns, which, according to it, represent 15% of all German storage caverns that could possibly store hydrogen in the future. The company has partnered with the German Aerospace Center's Institute of Networked Energy Systems to build an underground storage cavern in salt rock in Rüdersdorf as part of a nearly EUR-10-million research project.

EWE began construction of the test cavern in February 2021 with the expectation that it will be filled with hydrogen for the first time in the spring of 2022. The cavern will have a capacity of 500 cubic metres and once completed, it will be able to store up to 6 tonnes of hydrogen.

The goal of the project is to determine how storage and relocation affect the quality of the hydrogen. EWE expects initial findings in the second half of 2022.

The company itself is investing about EUR 4 million in the project, while the rest comes in the form of a grant from the German Federal Ministry of Transport and Digital Infrastructure through the National Innovation Programme for Hydrogen and Fuel Cell Technology.

EWE's ultimate objective is to use caverns with a capacity of 500,000 cubic metres for large-scale hydrogen storage in the future.

Coega Green Ammonia Plant project (South Africa)

At the end of 2021, Hive Hydrogen and Linde announced plans for a USD-4.6-billion green ammonia project at the Coega Special Economic Zone alongside the Port of Ngqura in Nelson Mandela Bay, South Africa.

The project was introduced as the world's largest green ammonia plant.

"The renewable energy and energy storage component alone will be the biggest project of its kind in Sub-Saharan Africa and one of the largest globally," Hive Energy CEO, Giles Redpath, said at the time.

If completed to its full envisaged capacity, the facility will produce 780,000 tonnes of ammonia per year for export to world markets. The plan involves the production of hydrogen by electrolysers running on renewable energy and the simultaneous extraction of nitrogen (N) from the air through an air separation unit. The hydrogen and nitrogen are then combined through ammonia synthesis to produce the ammonia, which is subsequently cooled, liquified and stored for export.

While the news release did not mention the exact renewable energy capacity that is planned to be deployed as part of the scheme, Hive Energy's website lists a South African green ammonia project at the Port of Elizabeth named Coega with a capacity of 1,350 MW.

Sinopec Xinjiang Kuqa Green Hydrogen Pilot Project (China)

China Petroleum & Chemical Corporation, better known as Sinopec, is already building a large-scale green hydrogen production plant with its dedicated storage facility in Xinjiang Uygur Autonomous Region.

The project is valued at a total of USD 471 million and envisages the installation of an eletrolyser with the capacity to produce 20,000 tonnes of green hydrogen per year using electricity generated by a new 300-MW solar plant. The complex will benefit from its own spherical hydrogen storage tank with the capacity to store 210,000 standard cubic metres of hydrogen. In addition, Sinopec will build hydrogen transmission pipelines with a capacity of 28,000 standard cubic metres per hour.

The project is seen to be finalised in June 2023. Upon completion, the output of the plant will be supplied to Sinopec Tahe Refining & Chemical.

Picture 3: Sinopec starts construction of a green hydrogen complex in China. Source: Sinopec.

5. CONCLUSION

In order to establish a hydrogen energy system, technology developers, project stakeholders and policymakers need to find address different challenges, including with hydrogen storage.

In its Hydrogen Program Plan, released in November 2020, the US Department of Energy lists a number of targets that have to be achieved:

- Lower-cost hydrogen storage systems
- Higher storage capacity, with reduced weight and volume
- Large-scale storage, including onsite bulk emergency supply and in geologic formations
- Optimised storage strategies for co-locating stored hydrogen with end-use applications to meet throughput and dynamic response requirements and reduce investment cost

The EU also emphasises on the fact that creating infrastructure for the transport and storage of hydrogen is crucial. It estimates that from now to 2030, about EUR 65 billion in investments will be needed for hydrogen transport, distribution and storage, as well as for hydrogen refueling stations. It notes, though, that the need for investment can be diminished by repurposing existing gas transport and storage infrastructure.

The EU's hydrogen strategy, adopted in July 2020, presents a three-phase approach for the period 2020-2050. Establishing larger-scale storage facilities and planning a pan-European hydrogen network is part of the second phase, which is planned for the period 2024-2030.

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