The challenges of Hydrogen Storage on a large scale

Olivier Rambert / Linda Febvre, from Engie Group

With the growing success of green hydrogen, the general trend is for increased hydrogen production and large quantities of storage.

Engie's projects have grown from a few kilos of hydrogen to the quest for large scale production and associated storage – e.g. several tons or tens of tons.

Although a positive sign for Engie's projects, it does inevitably result in challenges in new storage methods and in risks management related to such facilities; particularly with hydrogen facilities being increasingly placed in the vicinity of general public sites. For example, a leak on hydrogen storage can generate significant thermal and overpressure effects on surrounding people/facilities in the event of ignition. Firewalls can be installed to protect individuals / infrastructure from thermal effects but, the adverse result is that this solution can increase the violence of an explosion in case of delayed ignition or confinement.

The manner of emergency intervention on a pool fire of hydrogen is also totally different from intervention on compressed gaseous hydrogen.

The first part of this presentation will explain different means to store hydrogen in large quantities.

The second part will present for each storage the specific risks generated.

The third and final part will explain how these risks can be addressed on a technical point of view by safety devices or by other solutions (separation distance, passive/active means, …).

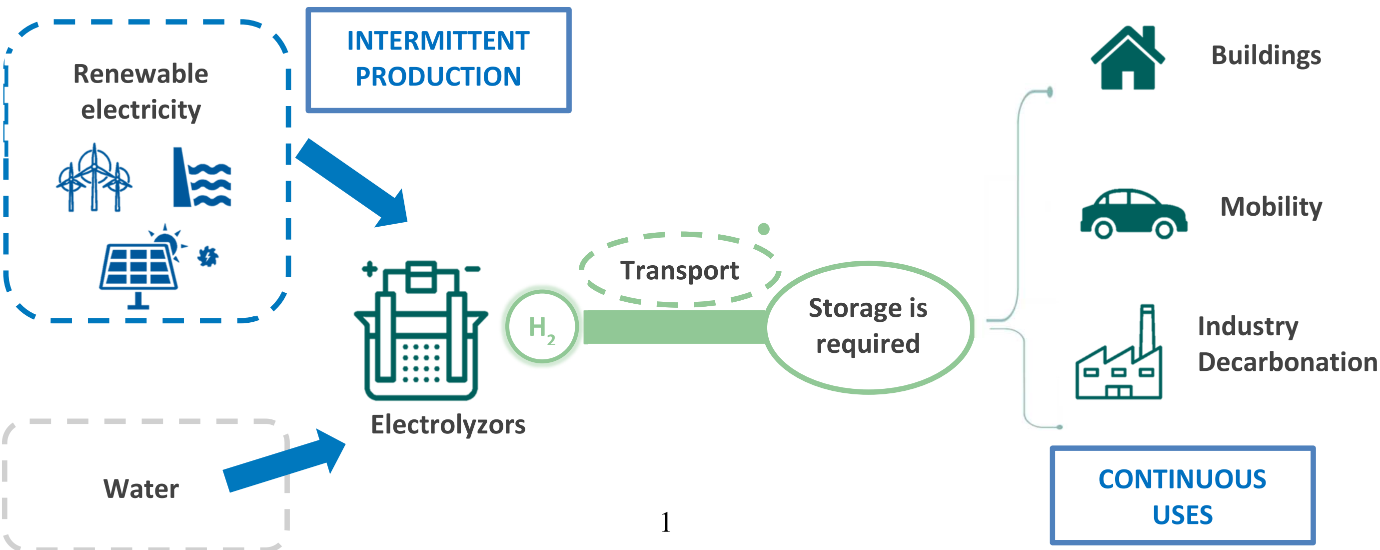
1. Storage of green hydrogen in large quantity

1.1. The need for storage of green hydrogen

With an ongoing transition to renewable and intermittent energy - such as solar and wind power -, new solutions to store electrical energy to balance the supply and demand are required. In addition, several sectors are currently looking to reduce their use of fossil fuels. In order to find solutions in both these cases, hydrogen may play an important role. However, whether production or transport, there will inevitably be a requirement for the storage of hydrogen.

The aim of the stationary storage of hydrogen can be for backup purposes as shown in figure 1. For example, in the event that there is a requirement for a continuous supply of hydrogen (industrial use such as a refinery, …) with an intermittent electricity source (solar, wind, …) there is a need to store in order to ensure that there is a sufficiently large storage of hydrogen available to supply the process even outside the periods of hydrogen production (night, …)

Figure 1: Need for hydrogen storage



1.2. Different available technologies for the storage of hydrogen

Storage of hydrogen on a large scale (of more than one hundred tonnes of hydrogen) is still relatively scarce nowadays . Such existing large scale storages are underground storage e.g. the salt caverns in Texas, USA and Teeside in the UK. However, this kind of storage is not possible everywhere and presents some drawbacks. Therefore, a broader discussion and evaluation of the available large-scale hydrogen storage options is necessary. This chapter aims to review and compare the available options for large-scale hydrogen storage.

To understand the challenges of large scale storage of hydrogen, it is first necessary to understand hydrogen itself: hydrogen has the lightest molecule and a very low density: 1 kg of hydrogen gas occupies over 11 m^3 at room temperature and atmospheric pressure. Therefore, for the storage of large scale quantities of hydrogen to be viable, it's storage density must be increased. This inevitably has an impact on risk; whether it be increased heat or pressure or multiplying the process steps.

There are a number of emerging technologies for the storage of hydrogen, for example adsorption onto or into a material e.g. liquified nitrogen and chemical bonding with chemical or metal hybrides. However, t**he primary focus of this paper is on the storage of gaseous and liquid hydrogen in its pure, molecular form.** These are the only types of hydrogen storage that are currently employed on any significant scale.

<u>Compressed hydrogen (gas):</u>
A compressed gas storage system has two main components: the storage compartment and the compressors needed to achieve the storage pressure.

Due to reasons of material properties and operating costs, large amounts of gaseous hydrogen are usually not stored at pressures exceeding 150 bar in above ground vessels and 200 bar in underground storages. As the storage pressures are limited, so are the achievable hydrogen storage densities: at 100 bar and 20 °C, the density of hydrogen gas is approximately 7.8 kg/m^3. The low hydrogen density leads to large storage and, thus, high investment costs. However, a lower storage pressure demands less compression work and, thus, operating costs.,

Large amounts of hydrogen **are already stored underground**: the already mentioned salt cavity storages in Teeside, UK (210 000 m^3), and Texas, USA (580 000 m^3), have proven the applicability of the approach. However, not all regions have the proper geological prerequisites for salt cavity storage, gas fields, and aquifers.

One alternative solution is to contain the stored gas in a **metal container**. While a metal container increases investment costs, it ensures the stability of the storage, the purity of stored hydrogen, and it can be applied independently of location. While there is little experience with the large-scale storage of hydrogen in metallic vessels, it is relatively common practice for natural gas, and the same types of vessels could be applied for the storage of hydrogen. Three main types of metallic vessels are currently used for the storage of larger amounts of natural gas:

1. Spherical with maximum storage pressures up to approximately 50 bar.
2. Pipe storage, with maximum storage pressures of approximately 100 bar.
3. Bullet storage with maximum storage pressures of approximately 150 bar.

Due to the higher storage pressure of hydrogen, the most promising option among these for the large-scale storage of hydrogen seems, according to studies undertaken in the context of Engie's projects, to be the **storage bullets**, as depicted in figure 2 below.

Figure 2: Hydrogen storage in bullets

Pipe storage has been applied for the storage of natural gas since the 1980s, mainly to manage peaks in demand for storage facilities with limited access to a natural gas grid. The construction of a pipe storage is relatively simple: a series of relatively short pipelines are laid down with sealed ends and diameters ranging up to around 1.4 m. The total length of pipeline may be several kilometers, usually positioned a couple of meters below the surface level. Using the pressures of existing pipe storages of natural gas, approximately 12 t of hydrogen could be stored per km of pipeline. However, the construction of hydrogen pipelines is more expensive than those for natural gas, mainly due to the phenomenon of embrittlement and pressure cycling negatively affecting the mechanical properties of steel materials over time, necessitating increased safety margins. Furthermore, the pipelines need to be welded to minimise leaks. However, this solution tends to be more acceptable to regulatory authorities when the pipe has a transport function; meaning that hydrogen is transferred from one point (production) to the end source (user/off-taker).

As shown in figure 3 below, the **storage of hydrogen in racks of vertical bottles (or horizontal tubes)** can be considered for large scale storage (up to several tons of hydrogen) but it presents some important difficulties: it requires extended space for the layout of the containers because the surfacic density on the ground is very low and because of the required separation distances between the containers to minimise potential domino effects. Moreover, there are additional complexities and risks to operate this kind of storage due to the numerous valves required to manipulate to fill and empty the different containers (for example 40 containers required for 15 tons). Bottles/tubes can be constructed either in metallic material or in CFRP (carbon fiber-reinforced plastic). CFRP is much lighter for transport and has good mechanical strength under high pressure (under 900 barg). But it is sensitive to high temperature (above 60°C) and needs to be protected from such specific conditions.

Figure 3: Photo from Tenaris Company: Rack of horizontal tubes of hydrogen

Liquefied hydrogen:

In addition to compression, the density of pure hydrogen may also be increased with liquefaction. Liquefaction has the advantage that very high hydrogen storage densities can be attained already at atmospheric pressure: the density of saturated liquid hydrogen at 1 bar is 70 kg/m3. Liquid hydrogen has mainly been evaluated as a hydrogen distribution medium, where its high density is a substantial advantage.

The primary concern for the storage of liquid hydrogen is the energy-intensive liquefaction process. There are two main fundamental reasons as to why the liquefaction of hydrogen requires a substantial input of energy: the extremely low boiling point of hydrogen (−253 °C at 1 bar) and the fact that hydrogen gas does not cool down during throttling processes (adiabatic, isenthalpic expansion) for temperatures above around −73 °C. The latter problem necessitates precooling in the liquefaction process, most often by the evaporation of liquid nitrogen.

Nevertheless, hydrogen liquefaction is reasonably well-established: the global installed hydrogen liquefaction capacity is around 355 tons per day (tpd); the largest plant currently in operation has a capacity of 34 tpd. The all-time largest hydrogen liquefaction plants were constructed for NASA during the 1950s-1970s; most more recently constructed plants are small in comparison (1–10 tpd). Nonetheless, even if the specific energy demand of liquefaction can be significantly lowered, the capital costs of a liquefaction plant are still a significant part of the overall costs of liquefaction, even for larger plants. For instance, it has been estimated that the capital investment constitutes around 40–50% of the specific liquefaction costs for a new 100 tpd liquefaction plant.

Figure 4: Example of a liquefied hydrogen storage

Liquid hydrogen storage vessels are most commonly double-walled with a high vacuum applied between the walls. The vacuum minimizes heat transfer via conduction and convection. The space between the vessel walls also contains additional materials such as alumina-coated polyester sheets. NASA operates the largest current storage vessels for liquid hydrogen at Cape Canaveral, USA; the amount of hydrogen stored in these vessels is 230–270 t. Construction of even larger spherical liquid hydrogen storage vessels should be possible with available technology, perhaps reaching storage capacities above 900 t. Despite the relative complexity of their construction, there are indications that liquid hydrogen storage tanks are less costly per weight of hydrogen stored than vessels for pressurized gaseous hydrogen on larger scales.

2. Specific risks generated and relevance of the different solutions for large scale storage

Here below are presented the main risks, maturity and relevance of the different technologies for a purpose of large scale storage of hydrogen.

2.1. Compressed hydrogen in bullets

Storage of hydrogen gas in bullets allows for storage of hydrogen at quite a high pressure (150 barg) and so, consequently, to a high density (about 15 kg/m^3). For example, 15 tons of hydrogen can be stored in a total capacity of 1 000 m^3 (4 bullets of 250 m^3). However, bullet solution is a significant source of hydrogen leak at this pressure and therefore the bullets need to be designed to stringent and demanding specifications in terms of material thickness, minimum and specific flanges, control of integrity…) to respond to the cycling of the inner pressure and potential embrittlement of the material by hydrogen. Given that one bullet can contain a large quantity of hydrogen (several tons), explosure to potential mechanical and dominos effects (thermal, overpressure) could generate disastrous safety consequences. For this reason, such a solution has to be protected by additional means. This solution will be developed further in the final section of this article.

2.2. Compressed hydrogen in racks of container

Storage of hydrogen gas in racks of containers allows for the storage of hydrogen under a high pressure (200 to 300 barg) and so to quite a high density (about 20 to 30 kg/m^3). Racks of containers (or tube trailers) are usually solutions that have been designed by companies for transportation purposes and so have only ever really been proven for this function. The problematic with this solution for large scale storage is that a rack solution has got a large footprint on the ground and the potential for domino effects between racks should be studied and safeguards installed (firewall, separation distance, …) to protect them from unwanted events (thermal and overpressure effects). This solution will be developed further in the final part of this article.

2.3. Compressed hydrogen in pipes

Storage of hydrogen gas in a transportation pipeline between the hydrogen production site and the end user is a potential option. . However, it may be challenging to justify to the local regulatory authorities, the storage of hydrogen in a pipeline to the exterior of the production site perimeter (and potentially in the public domain) without the assoicated function of transportation. Moreover, pipeline solution is an important source of hydrogen leaks at this pressure and requires (as bullets) to be designed specifically according to stringent and demanding specifications (material thickness, minimum and specific flanges, control of integrity…) to manage the cycling of the inner pressure and embrittlement of material by hydrogen. Furthermore, a pipeline solution is limited to projects with a particular routing and one end user. Given the probable permitting and technical issues, this issue is discounted from this paper and will not be developed further.

2.4. Compressed hydrogen in underground cavity

Storage of hydrogen gas in an underground cavity presents a risk of leak due to high pressure inside storage. This risk is limited mainly to surface facilities (compression, …). Building a cavity for storage hydrogen is not possible everywhere: it depends on the local geology and stability of the ground. Moreover, it requires a very high CAPEX and specific skills to build such a cavity. It is much easier to use an existing cavity used previously for another gas (natural gas, …). This solution is currently being studied but not considered mature enough for development in imminent projects and so is discounted from this paper.

2.5. Liquefied hydrogen

Liquefied stored hydrogen has the big advantage not to be under significant pressure. This limits the risk of hydrogen leak through walls of tank. Liquefied hydrogen has to be cooled down at -253°C and loss of cooling can bring transformation. Thus, hydrogen is stored in a double walled isolated atmospheric tank in order to limit the loss of heat through the walls.

2.6. Synthesis of the main storage solutions features and risks

The **table 1** below provides a synthesis of the advantages and disadvantages of the different hydrogen storage solutions:

Storage solution	Safety aspect	Economical aspect	Maturity of the technology
Compressed GH2 in bullets	High risk of leak, jet fire and explosion related to high pressure (150 barg) with large quantity in only one capacity Can be buried to protect bullets from dominos effects	Need a significant metallic wall thickness for mechanical strength regarding high pressure **Can be used for large scale**	-
Compressed GH2 in racks of containers	High risk of leak, jet fire and explosion related to high pressure (up to 300 barg)	Requires large space for layout to take into account dominos effects Need a significant metallic wall thickness for mechanical strength regarding high pressure **Can be used for large scale**	++
Compressed GH2 in pipes	High risk of leak, jet fire and explosion related to high pressure (up to 100 barg) on public domain	Should be authorized only to transport H2 from one point to another different one Need a significant metallic wall thickness for mechanical strength regarding high pressure	+
Compressed GH2 in underground cavity	High risk of leak, jet fire and explosion related to high pressure	Not a good maturity Not possible everywhere **Can be used for large scale**	+
Cryogenic tank (LH2)	Less risk related to compressed GH2 Complex liquefaction facilities Risk of pool fire	Requires important energy to liquefy GH2 **Can be used for large scale**	+

Table 1: Safety aspects according to the solution of hydrogen storage

3. Risks and typical safeguards associated with main hydrogen storage solutions

3.1. Compressed hydrogen

Bullets/Racks of bottles-tubes

The risk of **hydrogen leak** is very high for compressed hydrogen storage due to the operating pressure ranges (several hundreds) and the relatively small size of the hydrogen molecule.

These **leaks can lead to a fire jet or an UVCE** (Unconfined Vapour cloud Explosion) in the event of an ignition source. The high pressure is a parameter which aggravates the consequences (high release flowrate, speed of the cloud, ignition easier at high pressure…).

It is therefore a real challenge to prevent leaks in such facilities: for **designing the hydrogen facilities according to relevant standards** (limitation of pressure, diameter of pipes, flanges, …), for **operating safely the facilities within the design parameters** and for **maintaining the tightness of equipment**.

Main barriers to **prevent leaks** of bullets/bottles are:

- Leak test after manual connection via a hose (bubble test, pressure test)
- Preventive maintenance of hoses/ pressure cycling follow up of bottles/tubes/bullets
- Preventive of mechanical shock on hydrogen storage
- Respect the design conditions (pressure, temperature, material)
- Minimize the consequences (outlets diameter/operating pressure, position of bottles, separation of containers with walls)

Internal overpressures should be prevented inside equipment through :

- safety instrumented functions based on pressure transmitters and safety PLC (Programmable Logic Controller) which prevents the build-up of pressure;
- safety devices should be installed on equipment like pressure safety valves (PSV) to prevent them from bursting. The PSV should be designed for credible scenarios (fire, internal overpressure, …). Their outlet should also be collected and vented to a safe location so as not to create an undesirable secondary event;
- In the event of a fire, equipment in approximity can heat up and internal pressure can increase quickly. Safety devices such as TPRDs (Temperature and Pressure Relief Devices) can protect the cylinders/equipment from bursting;
- Water deluge spray fixed system above sensitive equipment can also protect them from the effects of thermal radiation;
- A radical solution to protect equipment from thermal effects in proximity is to bury equipment underground or under a layer of protection (earth, concrete…)

In the event of the failure of preventive measures, it is required to detect hydrogen in atmosphere in particular when facilities are enclosed. Typical detectors for hydrogen gas are catalytic detectors and ultrasound detectors; the latter are more expensive but considered to have greater coverage and accuracy. Relevant fire detection system (IR/UV) is also required to detect a jet fire in the event of ignition.

Sources of ignition must be avoided in the proximity of the hydrogen facilities through the selection of specific equipment (ATEX design, grounding, lightning protection, …).

The following specific barriers/arrangement should be studied and installed for protecting from **jet fire**:

- Separation distances between HP storage and other critical equipment
- Fire walls between HP storage and other critical equipment

Some specific barriers/arrangement should be studied and installed for protecting from **UVCE**:

- Non confinement of HP storage area as far as possible possible (outdoor storage)
- The undertaking of CFD calculation studies to predict real overpressure generated by a UVCE taking into account obstacles in near field (firewalls, racks of tubes…)

Underground storage in cavity

Some specific barriers are also required to address risks specific to **underground hydrogen storage**: tightness of the walls, monitoring of the pressure inside the cavity, monitoring of the stability of the cavity along the time, venting in case of overpressure.

Hydrogen storage in cavity is not a practicable solution in the majority of hydrogen development projects hence it has not been developed further in this article.

3.2. Liquefied hydrogen

Liquefied hydrogen tank is subject to pool fire in the event of a release and spreading of LH2 if ignited. The installation of a fixed foam system could help to extinguish a hydrogen pool fire.

Furthermore, a limitation of the surface of the bund is required to limit the evaporation of hydrogen in case of liquid leak.

Liquefied solution is not a common solution in current projects and hence has not been developed further in this article.

Conclusion of the article

In conclusion, the storage and transfer of hydrogen is currently a weak link in the scale up of the hydrogen chain and therefore merits attention.

It is clear that there is not only one possible technology for the large scale storage of hydrogen. The current solution favoured by the majority of developers is compressed hydrogen in racks of bottles/tubes. Other solutions are under development (bullets, underground cavity). Some liquefaction facilities exist but are fully optimized for large quantities of hydrogen (several thousands of tons) and for continuous hydrogen production.

For safety reasons, it is deemed essential that attention is given to the location of storage equipment, separation distances, potential for dominos effects, integrated design safety functions. Furthermore, many standard off the shelf storage facilities such as bottles in racks do not necessarily incorporate the design functions listed above and therefore should be challenged. Lastly, it is recommended that detailed safety studies such as CFD studies are performed to understand the potential consequences in the event of the release of hydrogen and to validate the layout of the storage arrangement.