The various hydrogen storage technologies

Analyst Brief – November 2021

Special focus on Liquid Organic Hydrogen Carriers

Constantly growing energy needs imply development of new power plant capacities. In 2019, global electricity domestic consumption exceeded 24,000 TWh[1] compared to 11,000 TWh ten years before. Climatic context leads us to develop new energy production facilities that do not harm the environment. But solar and wind intermittency imply a new constraint on immediate electricity consumption or storage for later use. Quantity of stored electricity compared to direct consumption is low: 800 GWh[2] in 2019. Large scale electricity storage solutions lack to face this growing renewable energy fluctuation. Several solutions already exist. Pumped hydraulic storage is the most widespread to store electricity (98%). Other means tend to develop, including battery storage or "Power-to-Gas-to-Power". P2G2P consists of using a temporary storage in a gaseous form of the electricity to release it later in the electrical form. Hydrogen is more and more considered as a promising vector for storing electrical energy.

Following the latest hydrogen trends, the hydrogen vector is strongly considered as a way to decarbonise a significant part of tomorrow usages. Several countries integrated it in their development plan. For instance, Australia, whose "H_2 under 2" objective aims to produce a kg of green hydrogen below 2 $[3]. Despite the CO_2 content of current hydrogen production processes, trend is to develop clean hydrogen, meaning hydrogen whom production does not emit harmful particles and comes from renewable sources. The idea is to develop massively such production within next years. The major reason why 98% of current hydrogen production is still CO_2 emitter is economic. Producing 1 kg of the renewable molecule costs between 5 and 30 €[4] (15 to 90 ct€/kWh), which is up to 19 times more expensive than the industrial molecule. Like photovoltaic industry a few years ago, "giga factories" of electrolysers are developing and will contribute to lower production costs. However, logistics involved in hydrogen should not be overlooked, as it is not necessarily consumed where it is produced. We must enable the storage of large hydrogen quantities and transport them in an efficient way. As you will understand, large-scale storage will play a fundamental role in the hydrogen economy of tomorrow.

[1] Global Energy Statistical Yearbook, Enerdata, 2020
[2] Energy Storage Market Report, US DOE, 2020
[3] Australia's pathway to $2 per kg hydrogen, ARENA, 2020
[4] Nouvelle énergie verte, ADEME

How is hydrogen stored?

Hydrogen is mostly stored in a tank either in liquid or gaseous form. It is also possible to integrate the molecule into materials through so-called absorption or adsorption processes. The choice of a storage system will therefore depend on logistical parameters (e.g., quantity, duration, and methods of transport) and economic criteria. Anyway, transporting such gas is expensive. To be economically meaningful, it is essential to increase the storage density of the gas. How can we compare hydrogen storage technologies and determine the most relevant versus logistics and economics parameters?

Several options exist:

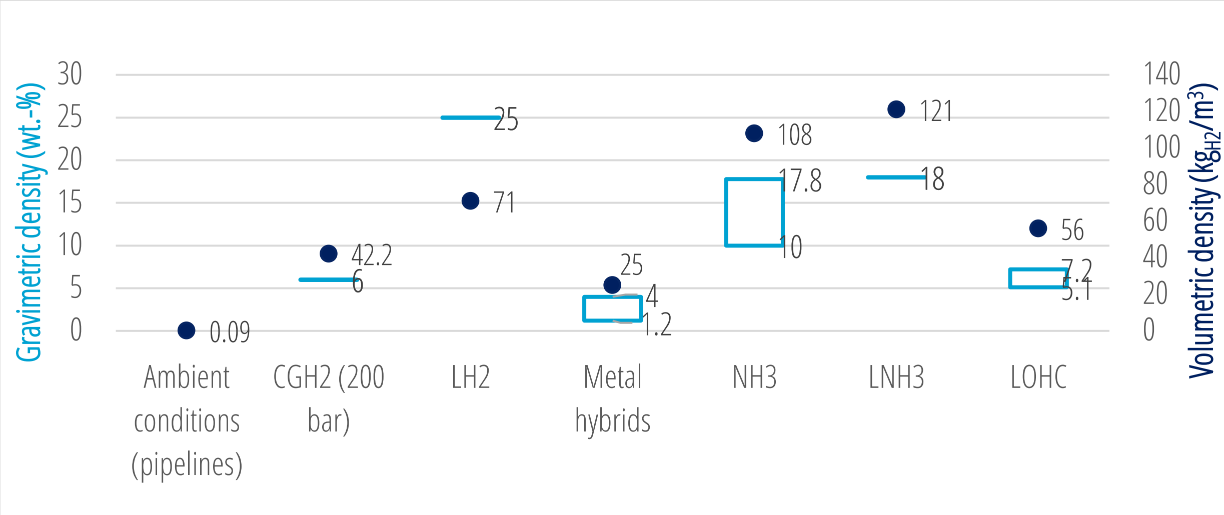
- **Hydrogen gaseous tank storage**: This widespread option offers only low storage densities and requires having extended safety zones to the high pressures plus the flammable nature of hydrogen.
- **Cryogenic liquid storage at -253°C**: Interesting way to increase storage density, it's however very energy-consuming both in the liquefaction and storage process. This solution is not compatible with long term storage due to transfer and evaporation losses. Indeed, 30 to 40% of hydrogen energy content is required in the liquefaction process[5] and its daily evaporation rate is between 1 and 15%, depending on the stored quantities[6].
- **Ammonia as an intermediary carrier**: The logistics benefits from its high volumetric density of hydrogen and its stability for long-term storage. Main danger is its toxicity: a less than 10 minutes exposure at 1%, concentration can be fatal.
- **Metallic hydrides storage**: Without compression step and feasible at pressures below 30 bar. They allow the storage of hydrogen for long periods without any risk of leakage if no heat source is provided. The challenge of this type of storage relates to the very low thermal conductivity of the system; it is necessary to optimize the heat transfer rate to reduce transfer times.
- **Liquid hydrogen carrier storage**: Currently only used at demonstration scale, this technology seems to be of interest for the storage, transport, and release of energy on a large scale.

It is interesting to compare these different storage medium according to their gravimetric density, noted wt.-%, which means here the capacity of a medium to integrate a part of hydrogen. As an example, a material with a gravimetric density of 1.5% and a mass of 60 kg will be able to integrate 0.9 kg of hydrogen.

[5] Ammonia to Green Hydrogen Project, 2019

[6] Boil-off losses along the LH2 pathway, Lawrence Livermore National Laboratory, 2018

Figure 1: Hydrogen storage medium capacity



Source: ***Compilation of data and research from Enerdata***

What are the hydrogen transport options?

- **Pipelines**: Low operational cost makes it possible to supply large volumes of hydrogen. However, the properties of hydrogen (corrosion, leaks, etc.) limit its injection into existing infrastructure since its long-term use degrades pipelines (embrittlement of steel). Pipeline transport is mainly considered in already existing structures because of important investments cost. Two kinds of structures can be used: 100% hydrogen dedicated pipelines and natural gas networks conversion, feasible within a limit of approx. 20% of hydrogen without degrading the structure[7].
- **Tube trailers**: Widespread option for mid-quantity transport (400 kg of H_2) in metallic tanks. Costly solution due to the pressurisation step plus trucks transport (maintenance, fuel, depreciation, etc.). Composite tanks recently entered the market allowing to store hydrogen at a higher pressure (220 bars vs 500 bars). More expensive than metallic ones their storage capacity can be up to 1,100 kg, allowing to further amortize operational costs.
- **Cryogenic**: First choice option to transport large quantities when there are no pipelines. No negligible downside, liquefaction step is costly and energy-consuming: process consumes more than 30% of hydrogen energetic content and leakages are really important (even more when the storage area is large). Liquid

[7] STRORENGY GRHYD project in Dunkerque

hydrogen road trucking makes more sense over long distances (>400 km) than gaseous trucking since larger amounts of hydrogen can be stored.

- **Ammonia vector use**: Few demonstration projects are planned. Ammonia production, transport, hydrogen dissociation and compression costs will need to be qualified, but ammonia transportation seems to make more economic sense than gaseous hydrogen transportation.
- **LOHC option**: Less expensive investment for trailer compared to previous options and also lower operational costs (maintenance) with the ability to compete on large-scale storage field.

Figure 2: Advantages and disadvantages of hydrogen storage and transport options

Storage-transport option	Advantages	Disadvantages
Liquid hydrogen *LH_2*	• Pure hydrogen • High storage density	• Storage temperature: -253°C • Investments to maintain the temperature • Energy-consuming process • Strong spontaneous discharge (leaks)
Ammonia *NH_3*	• Stability • Existing infrastructures • Pressure: ~10 bars	• Toxic molecule • High temperature and not mature cracking
Liquid Organic Hydrogen Carriers *LOHC*	• Existing infrastructures • Atmospheric pressure • Storage viability >1 year	• Energy requirement to release the hydrogen • Liquid carrier repatriation to the point of dispatch

Source: ***Compilation of data and research from Enerdata***

Focus on liquid hydrogen carriers

What characteristics?

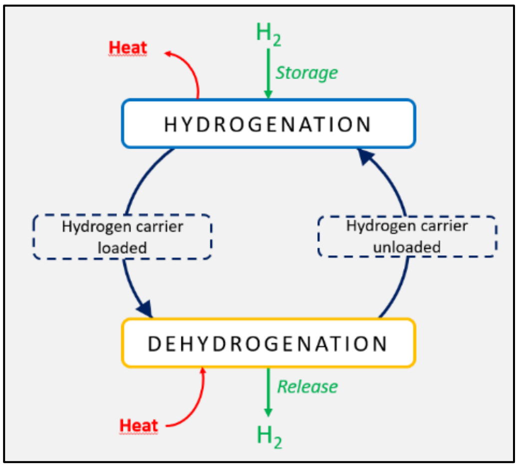
LHC principle is using a reversible chemical conversion process allowing to store hydrogen in a different chemical state from molecular hydrogen: the hydrogen is linked with a liquid.

Liquid organic carriers (LOHC), a subset of liquid carriers, seem promising for hydrogen storage and transportation.

Process is made of two steps:

- The hydrogenation (LOHC+) allowing to load hydrogen into a liquid carrier. In this state, the loaded carrier can be stored and distribute without any losses.
- If hydrogen is required, carrier can be unloaded independently of storage duration and location. This is called the dehydrogenation step (LOHC-).

Figure 3: Loading and unloading steps of hydrogen into and out of a carrier



Source: C ***Compilation of data and research from Enerdata***

Several carriers can load hydrogen.

HYDROGENIOUS and H_2 Industries players are using the liquid carrier DBT (Dibenzyl Toluene) which the advantage is currently being widely used as a heat transfer fluid and being commercialised on average at 5 € per kg[8]. DBT has the following benefits: there is no explosion nor flammability risk. The molecule toxicity is low compared to diesel or gasoline and its liquid state at ambient temperature allows to target mobility applications – no need to undertake constraining processes. However, liquid organic carriers tend to degrade over time with carbon emissions. Silicon-based carriers containing no carbon recently went off. The French start-up HySiLabs positioned on this field, uses a silicon-based carrier called "HydroSil".

[8] LOHC production cost estimation study, FCH-JU, 2019

Hydrogenious[9] estimated that one truck trailer can load up to:

- 400 kg of gaseous hydrogen at 200 bars,
- 1,800 kg of hydrogen with LOHC using DBT,
- 3,300 kg of liquid hydrogen at -253°C.

Carried out under ambient conditions, LOHC transportation technology seems relatively not constraining. Large-scale hydrogen quantities can be safely transported and in a flexible way. Trains and super tanker boats are being considered to transport several tonnes of hydrogen in the future.

What status for LOHC technology?

However promising, LOHC projects are still very rare and at demonstration phasis. Following costs are likely to limit its expansion for now: unloading process require energy, hydrogen purification and resend of the carrier liquid to the point of dispatch. An economic analysis carried out by the European Commission indicates that the costs of releasing the hydrogen contained in the carrier represents more than two thirds of the total transport cost[10].

It is now fair to consider which hydrogen storage-transport technology makes sense depending on logistical aspects. Take the advantages and disadvantages earlier enounced and add two more reading keys: distance and transport duration. We can conclude that:

- Pipelines are relevant for transporting large amounts of hydrogen for as many km as the network extends.
- Cryogenic option is suited for longer distances but is limited by duration. After about ten days, too much of the hydrogen will have evaporated because of the leaks.
- Liquid carriers make sense over very large distances and without time limitation because of the no spontaneous leaks technology. Limitation is about the unloading energy cost.

[9] Hydrogenious, LOHC technology supplier
[10] Assessment of Hydrogen Delivery Options, 2021

Figure 4: Comparison of storage-transport technologies

	Pipelines	Cryogenic	Liquid carriers
Long distances	+	+	++
Duration limitation	-	++	-
CAPEX	++	++	-
OPEX	-	++	++ (Highly depending on electricity cost)

Source: **Compilation of data and research from Enerdata**

LOHC technology seems relevant firstly on niche markets as for example transport over long time and distances. This kind of scenario can be considered in large hydrogen import contracts. Germany has just announced its agreement to import large hydrogen quantities from Australia. The port distance from Perth to Hamburg of over 20,000 km and the 30-day journey make cryogenic transport unimaginable and carrier transport appropriate[11].

[11] Considering a speed of 15 nautical knots, i.e., around 30 km/h