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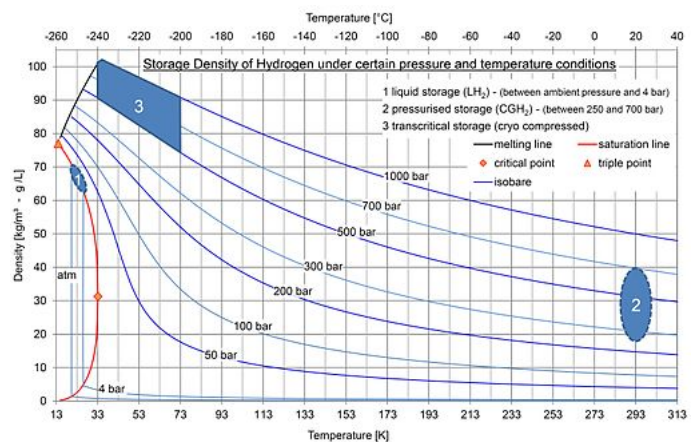
Compressed hydrogen

Compressed hydrogen is a storage form where hydrogen gas is kept under pressures to increase the storage density. Compressed hydrogen in hydrogen tanks at 350 bar (5,000 psi) and 700 bar (10,000 psi) is used for hydrogen tank systems in vehicles, based on type IV carbon-composite technology.^[3] Car manufacturers have been developing this solution, such as Honda^[4] or Nissan.^[5]

Liquid hydrogen

BMW has been working on liquid hydrogen tanks for cars, producing for example the BMW Hydrogen 7. Japan has liquid hydrogen (LH2) storage at a tanker port in Kobe, and are anticipated to receive the first shipment of liquid hydrogen via LH2 carrier in 2020.^[6] Hydrogen is liquified by reducing its temperature to -253°C , similar to liquified natural gas (LNG) which is stored at -162°C . A potential efficiency loss of 12.79% can be achieved, or 4.26kWh/kg out of 33.3kWh/kg.^[7]

Proposals and research



net storage density of hydrogen

Hydrogen storage technologies can be divided into physical storage, where hydrogen molecules are stored (including pure hydrogen storage via compression and liquefaction), and chemical storage, where hydrides are stored.

Chemical storage

Chemical storage could offer high storage performance due to the strong binding of hydrogen and the high storage densities. However, the regeneration of storage material is still an issue. A large number of chemical storage systems are under investigation, which involve hydrolysis reactions, hydrogenation/dehydrogenation reactions, ammonia borane and other boron hydrides, ammonia, and alane etc.^[8] Storage in hydrocarbons may also be successful in overcoming the issue with low density. For example, supercritical hydrogen at 30 °C and 500 bar only has a density of 15.0 mol/L while methanol has a density of 49.5 mol H₂/L methanol and saturated dimethyl ether at 30 °C and 7 bar has a density of 42.1 mol H₂/L dimethyl ether. These liquids would use much smaller, cheaper, safer storage tanks. The most promising chemical approach is electrochemical hydrogen storage, as the release of hydrogen can be controlled by the applied electricity.^[9] Most of the materials listed below can be directly used for electrochemical hydrogen storage.

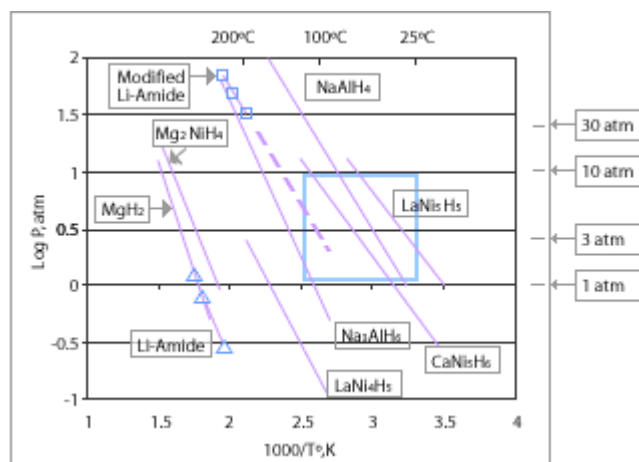
Metal hydrides

Metal hydrides, such as MgH₂, NaAlH₄, LiAlH₄, LiH, LaNi₅H₆, TiFeH₂ and palladium hydride, with varying degrees of efficiency, can be used as a storage medium for hydrogen, often reversibly.^[10] Some are easy-to-fuel liquids at ambient temperature and pressure, others are solids which could be turned into pellets. These materials have good energy density, although their specific energy is often worse than the leading hydrocarbon fuels.

Most metal hydrides bind with hydrogen very strongly. As a result, high temperatures around 120 °C (248 °F) – 200 °C (392 °F) are required to release their hydrogen content. This energy cost can be reduced by using alloys which consists of a strong hydride former and a weak one such as in LiNH₂, LiBH₄ and NaBH₄.^[11] These are able to form weaker bonds, thereby requiring less input to release stored hydrogen. However, if the interaction is too weak, the pressure needed for rehydriding is high, thereby eliminating any energy savings. The target for onboard hydrogen fuel systems is roughly <100 °C for release and <700 bar for recharge (20–60 kJ/mol H₂).^[12]

An alternative method for reducing dissociation temperatures is doping with activators. This has been successfully used for aluminium hydride but its complex synthesis makes it undesirable for most applications as it is not easily recharged with hydrogen.^[13]

Currently the only hydrides which are capable of achieving the 9 wt% gravimetric goal for 2015 (see chart above) are limited to lithium, boron and aluminium based compounds; at least one of the first-row elements or Al must be added. Research is being done to determine new compounds which can be used to meet these requirements.



Metal hydride hydrogen storage

Proposed hydrides for use in a hydrogen economy include simple hydrides of magnesium^[14] or transition metals and complex metal hydrides, typically containing sodium, lithium, or calcium and aluminium or boron. Hydrides chosen for storage applications provide low reactivity (high safety) and high hydrogen storage densities. Leading candidates are lithium hydride, sodium borohydride, lithium aluminium hydride and ammonia borane. A French company McPhy Energy is developing the first industrial product, based on magnesium hydride, already sold to some major clients such as Iwatani and ENEL.

New Scientist reported that Arizona State University is investigating using a borohydride solution to store hydrogen, which is released when the solution flows over a catalyst made of ruthenium.^[15] Researchers at University of Pittsburgh and Georgia Tech performed extensive benchmarking simulations on mixtures of several light metal hydrides to predict possible reaction thermodynamics for hydrogen storage.^{[16][17][18]}

Non-metal hydrides

The Italian catalyst manufacturer Acta has proposed using hydrazine as an alternative to hydrogen in fuel cells. As the hydrazine fuel is liquid at room temperature, it can be handled and stored more easily than hydrogen. By storing it in a tank full of a double-bonded carbon-oxygen carbonyl, it reacts and forms a safe solid called hydrazone. By then flushing the tank with warm water, the liquid hydrazine hydrate is released. Hydrazine breaks down in the cell to form nitrogen and hydrogen which bonds with oxygen, releasing water.^[19]

Carbohydrates

Carbohydrates (polymeric C₆H₁₀O₅) releases H₂ in a bioreformer mediated by the enzyme cocktail—cell-free synthetic pathway biotransformation. Carbohydrate provides high hydrogen storage densities as a liquid with mild pressurization and cryogenic constraints: It can also be stored as a solid powder. Carbohydrate is the most abundant renewable bioresource in the world.

In May 2007 biochemical engineers from the Virginia Polytechnic Institute and State University and biologists and chemists from the Oak Ridge National Laboratory announced a method of producing high-yield pure hydrogen from starch and water.^[20] In 2009, they demonstrated to produce nearly 12 moles of hydrogen per glucose unit from cellulosic materials and water.^[21] Thanks to complete conversion and modest reaction conditions, they propose to use carbohydrate as a high energy density hydrogen carrier with a density of 14.8 wt%.^[22]

Synthesized hydrocarbons

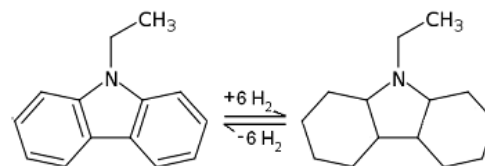
An alternative to hydrides is to use regular hydrocarbon fuels as the hydrogen carrier. Then a small hydrogen reformer would extract the hydrogen as needed by the fuel cell. However, these reformers are slow to react to changes in demand and add a large incremental cost to the vehicle powertrain.

Direct methanol fuel cells do not require a reformer, but provide a lower energy density compared to conventional fuel cells, although this could be counterbalanced with the much better energy densities of ethanol and methanol over hydrogen. Alcohol fuel is a renewable resource.

Solid-oxide fuel cells can operate on light hydrocarbons such as propane and methane without a reformer, or can run on higher hydrocarbons with only partial reforming, but the high temperature and slow startup time of these fuel cells are problematic for automotive applications.

Liquid organic hydrogen carriers (LOHC)

Unsaturated organic compounds can store huge amounts of hydrogen. These *Liquid Organic Hydrogen Carriers* (LOHC) are hydrogenated for storage and dehydrogenated again when the energy/hydrogen is needed. Research on LOHC was concentrated on cycloalkanes at an early stage, with its relatively high hydrogen capacity (6-8 wt %) and production of CO_x-free hydrogen.^[23]



Heterocyclic aromatic compounds (or N-Heterocycles) are also appropriate for this task. A compound that stands in the focus of the current LOHC research is N-ethylcarbazole (NEC)^[24] but many others do exist.^[25] More recently dibenzyltoluene, which is already industrially used as a heat transfer fluid in industry, was identified as potential LOHC. With a wide liquid range between -39 °C (melting point) and 390 °C (boiling point) and a hydrogen storage density of 6.2 wt% dibenzyltoluene is ideally suited as LOHC material.^[26] More recently, formic acid (FA) has been suggested as a promising hydrogen storage material with a 4.4wt% hydrogen capacity.^[27]

Using LOHCs relatively high gravimetric storage densities can be reached (about 6 wt-%) and the overall energy efficiency is higher than for other chemical storage options such as producing methane from the hydrogen.^[28]

▪ Cycloalkanes

Cycloalkanes reported as LOHC include cyclohexane, methyl-cyclohexane and decalin. The dehydrogenation of cycloalkanes is highly endothermic (63-69 kJ/mol H₂), which means this process requires high temperature.^[23] Dehydrogenation of decalin is the most thermodynamically favored among the three cycloalkanes, and methyl-cyclohexane is second because of the presence of the methyl group.^[29] Research on catalyst development for dehydrogenation of cycloalkanes has been carried out for decades. Nickel (Ni), Molybdenum (Mo) and Platinum (Pt) based catalysts are highly investigated for dehydrogenation. However, coking is still a big challenge for catalyst's long-term stability.^{[30][31]}

▪ N-Heterocycles

Both hydrogenation and dehydrogenation of LOHCs requires catalysts.^[23] It was demonstrated that replacing hydrocarbons by hetero-atoms, like N, O etc. improves reversible de/hydrogenation properties. The temperature required for hydrogenation and dehydrogenation of drops significantly with increasing numbers of heteroatoms.^[32] Among all the N-heterocycles, the saturated-unsaturated pair of dodecahydro-N-ethylcarbazole (12H-NEC) and NEC has been considered as a promising candidate for hydrogen storage with a fairly large hydrogen content (5.8wt%).^[33] The figure on the top right shows dehydrogenation and hydrogenation of the 12H-NEC and NEC pair. The standard catalyst for NEC to 12H-NEC is Ru and Rh based. The selectivity of hydrogenation can reach 97% at 7 MPa and 130 °C-150 °C.^[23] Although N-Heterocycles can optimize the unfavorable thermodynamic properties of cycloalkanes, a lot of issues remain unsolved, such as high cost, high toxicity and kinetic barriers etc.^[23]

▪ Formic acid

In 2006 researchers of EPFL, Switzerland, reported the use of formic acid as a hydrogen storage material.^[34] Carbon monoxide free hydrogen has been generated in a very wide pressure range (1–600 bar). A homogeneous catalytic system based on water-soluble ruthenium catalysts selectively decompose HCOOH into H₂ and CO₂ in aqueous solution.^[35] This catalytic system overcomes the limitations of other catalysts (e.g. poor stability, limited catalytic lifetimes, formation of CO) for the decomposition of formic acid making it a viable hydrogen storage material.^[36] And the co-product of this decomposition, carbon dioxide, can be used as hydrogen vector by hydrogenating it back to formic acid in a second step. The catalytic hydrogenation of CO₂ has long been studied and efficient procedures have been developed.^{[37][38]} Formic

acid contains 53 g L^{-1} hydrogen at room temperature and atmospheric pressure. By weight, pure formic acid stores 4.3 wt% hydrogen. Pure formic acid is a liquid with a flash point $69 \text{ }^{\circ}\text{C}$ (cf. gasoline $-40 \text{ }^{\circ}\text{C}$, ethanol $13 \text{ }^{\circ}\text{C}$). 85% formic acid is not flammable.

Ammonia

Ammonia (NH_3) releases H_2 in an appropriate catalytic reformer. Ammonia provides high hydrogen storage densities as a liquid with mild pressurization and cryogenic constraints: It can also be stored as a liquid at room temperature and pressure when mixed with water. Ammonia is the second most commonly produced chemical in the world and a large infrastructure for making, transporting, and distributing ammonia exists. Ammonia can be reformed to produce hydrogen with no harmful waste, or can mix with existing fuels and under the right conditions burn efficiently. Since there is no carbon in ammonia, no carbon by-products are produced; thereby making this possibility a "carbon neutral" option for the future. Pure ammonia burns poorly at the atmospheric pressures found in natural gas fired water heaters and stoves. Under compression in an automobile engine it is a suitable fuel for slightly modified gasoline engines. Ammonia is a toxic gas at normal temperature and pressure and has a potent odor.^[39]

In September 2005 chemists from the Technical University of Denmark announced a method of storing hydrogen in the form of ammonia saturated into a salt tablet. They claim it will be an inexpensive and safe storage method.^[40]

Amine borane complexes

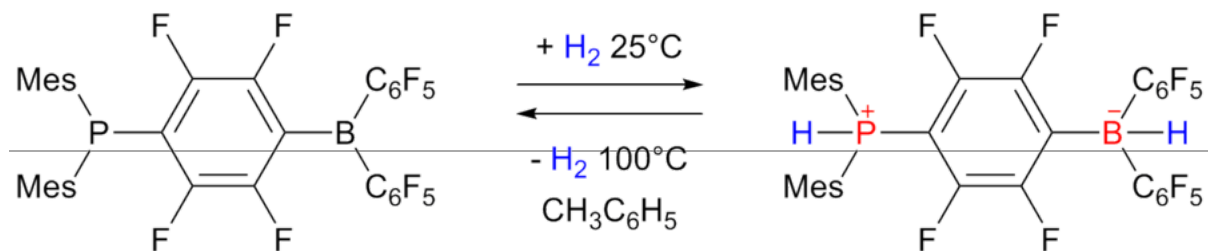
Prior to 1980, several compounds were investigated for hydrogen storage including complex borohydrides, or aluminohydrides, and ammonium salts. These hydrides have an upper theoretical hydrogen yield limited to about 8.5% by weight. Amongst the compounds that contain only B, N, and H (both positive and negative ions), representative examples include: amine boranes, boron hydride ammoniates, hydrazine-borane complexes, and ammonium octahydrotriborates or tetrahydroborates. Of these, amine boranes (and especially ammonia borane) have been extensively investigated as hydrogen carriers. During the 1970s and 1980s, the U.S. Army and Navy funded efforts aimed at developing hydrogen/deuterium gas-generating compounds for use in the HF/DF and HCl chemical lasers, and gas dynamic lasers. Earlier hydrogen gas-generating formulations used amine boranes and their derivatives. Ignition of the amine borane(s) forms boron nitride (BN) and hydrogen gas. In addition to ammonia borane (H_3BNH_3), other gas-generators include diborane diammoniate, $\text{H}_2\text{B}(\text{NH}_3)_2\text{BH}_4$.

Imidazolium ionic liquids

In 2007 Dupont and others reported hydrogen-storage materials based on imidazolium ionic liquids. Simple alkyl(aryl)-3-methylimidazolium N-bis(trifluoromethanesulfonyl)imidate salts that possess very low vapour pressure, high density, and thermal stability and are not inflammable can add reversibly 6–12 hydrogen atoms in the presence of classical Pd/C or IrO nanoparticle catalysts and can be used as alternative materials for on-board hydrogen-storage devices. These salts can hold up to 30 g L^{-1} of hydrogen at atmospheric pressure.^[41]

Phosponium borate

In 2006 researchers of University of Windsor reported on reversible hydrogen storage in a non-metal phosponium borate frustrated Lewis pair:^{[42][43][44]}



The phosphino-borane on the left accepts one equivalent of hydrogen at one atmosphere and 25 °C and expels it again by heating to 100 °C. The storage capacity is 0.25 wt% still rather below the 6 to 9 wt% required for practical use.

Carbonite substances

Research has proven that graphene can store hydrogen efficiently. After taking up hydrogen, the substance becomes graphane. After tests, conducted by dr André Geim at the University of Manchester, it was shown that not only can graphene store hydrogen easily, it can also release the hydrogen again, after heating to 450 °C.^{[45][46]}

Metal-organic frameworks

Metal-organic frameworks represent another class of synthetic porous materials that store hydrogen and energy at the molecular level. MOFs are highly crystalline inorganic-organic hybrid structures that contain metal clusters or ions (secondary building units) as nodes and organic ligands as linkers. When guest molecules (solvent) occupying the pores are removed during solvent exchange and heating under vacuum, porous structure of MOFs can be achieved without destabilizing the frame and hydrogen molecules will be adsorbed onto the surface of the pores by physisorption. Compared to traditional zeolites and porous carbon materials, MOFs have very high number of pores and surface area which allow higher hydrogen uptake in a given volume. Thus, research interests on hydrogen storage in MOFs have been growing since 2003 when the first MOF-based hydrogen storage was introduced. Since there are infinite geometric and chemical variations of MOFs based on different combinations of SBUs and linkers, many researches explore what combination will provide the maximum hydrogen uptake by varying materials of metal ions and linkers.

In 2006, chemists at UCLA and the University of Michigan have achieved hydrogen storage concentrations of up to 7.5 wt% in MOF-74 at a low temperature of 77 K.^{[47][48]} In 2009, researchers at University of Nottingham reached 10 wt% at 77 bar (1,117 psi) and 77 K with MOF NOTT-112.^[49] Most articles about hydrogen storage in MOFs report hydrogen uptake capacity at a temperature of 77K and a pressure of 1 bar because these conditions are commonly available and the binding energy between hydrogen and the MOF at this temperature is large compared to the thermal vibration energy. Varying several factors such as surface area, pore size, catenation, ligand structure, and sample purity can result in different amounts of hydrogen uptake in MOFs.

Encapsulation

Cella Energy technology is based around the encapsulation of hydrogen gas and nano-structuring of chemical hydrides in small plastic balls, at room temperature and pressure.^[50]

Physical storage

In this case hydrogen remains in physical forms, i.e., as gas, supercritical fluid, adsorbate^{[51][52]}, or molecular inclusions. Theoretical limitations and experimental results are considered ^[53] concerning the volumetric and gravimetric capacity of glass microvessels, microporous, and nanoporous media, as well as safety and refilling-time demands.

Activated carbons

Activated carbons are highly porous amorphous carbon materials with high apparent surface area^{[51][52]}. Hydrogen physisorption can be increased in these materials by increasing the apparent surface area and optimizing pore diameter to around 7 Å.^[54] These materials are of particular interest due to the fact that they can be made from waste materials, such as cigarette butts which have shown great potential as precursor materials for high-capacity hydrogen storage materials.^{[55][56]}

Cryo-compressed

Cryo-compressed storage of hydrogen is the only technology that meets 2015 DOE targets for volumetric and gravimetric efficiency (see "C₂H₂" on slide 6 in ^[57]).

Furthermore, another study has shown that cryo-compressed exhibits interesting cost advantages: ownership cost (price per mile) and storage system cost (price per vehicle) are actually the lowest when compared to any other technology (see third row in slide 13 of ^[58]). For example, a cryo-compressed hydrogen system would cost \$0.12 per mile (including cost of fuel and every associated other cost), while conventional gasoline vehicles cost between \$0.05 and \$0.07 per mile.

Like liquid storage, cryo-compressed uses cold hydrogen (20.3 K and slightly above) in order to reach a high energy density. However, the main difference is that, when the hydrogen would warm-up due to heat transfer with the environment ("boil off"), the tank is allowed to go to pressures much higher (up to 350 bars versus a couple of bars for liquid storage). As a consequence, it takes more time before the hydrogen has to vent, and in most driving situations, enough hydrogen is used by the car to keep the pressure well below the venting limit.

Consequently, it has been demonstrated that a high driving range could be achieved with a cryo-compressed tank : more than 650 miles (1,050 km) were driven with a full tank mounted on an hydrogen-fueled engine of Toyota Prius.^[59] Research is still on its way in order to study and demonstrate the full potential of the technology.^[60]

As of 2010, the BMW Group has started a thorough component and system level validation of cryo-compressed vehicle storage on its way to a commercial product.^[61]

Carbon nanotubes

Hydrogen carriers based on nanostructured carbon (such as carbon buckyballs and nanotubes) have been proposed. However, since Hydrogen usually amounts up to ~3.0-7.0 wt% at 77K which is far from the value set by US department of Energy (6 wt% at nearly ambient conditions), it makes carbon materials poor candidates for hydrogen storage.

Clathrate hydrates

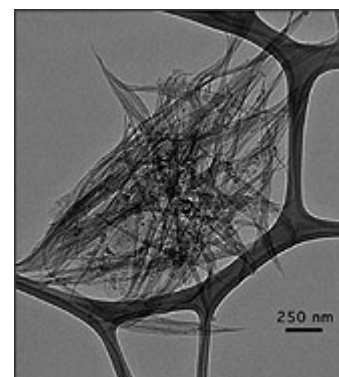
H₂ caged in a clathrate hydrate was first reported in 2002, but requires very high pressures to be stable. In 2004, researchers from Delft University of Technology and Colorado School of Mines showed solid H₂-containing hydrates could be formed at ambient temperature and 10s of bar by adding small amounts of promoting substances such as THF.^[62] These clathrates have a theoretical maximum hydrogen densities of around 5 wt% and 40 kg/m³.

Glass capillary arrays

A team of Russian, Israeli and German scientists have collaboratively developed an innovative technology based on glass capillary arrays for the safe infusion, storage and controlled release of hydrogen in mobile applications.^{[63][64]} The C.En technology has achieved the United States Department of Energy (DOE) 2010 targets for on-board hydrogen storage systems.^[65] DOE 2015 targets can be achieved using flexible glass capillaries and cryo-compressed method of hydrogen storage.^[66]

Glass microspheres

Hollow glass microspheres (HGM) can be utilized for controlled storage and release of hydrogen.^{[67][68]}



Carbon nanotubes

Stationary hydrogen storage

Unlike mobile applications, hydrogen density is not a huge problem for stationary applications. As for mobile applications, stationary applications can use established technology:

- Compressed hydrogen (CGH₂) in a hydrogen tank^[69]
- Liquid hydrogen in a (LH₂) cryogenic hydrogen tank
- Slush hydrogen in a cryogenic hydrogen tank

Underground hydrogen storage

Underground hydrogen storage is the practice of hydrogen storage in underground caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen have been stored in underground caverns by ICI for many years without any difficulties.^[70] The storage of large quantities of liquid hydrogen underground can function as grid energy storage. The round-trip efficiency is approximately 40% (vs. 75-80% for pumped-hydro (PHES)), and the cost is slightly higher than pumped hydro, if only a limited number of hours of storage is required.^[71] Another study referenced by a European staff working paper found that for large scale storage, the cheapest option is hydrogen at €140/MWh for 2,000 hours of storage using an electrolyser, salt cavern storage and combined-cycle power plant.^[72] The European project Hyunder^[73] indicated in 2013 that for the storage of wind and solar energy an additional 85 caverns are required as it cannot be covered by PHES and CAES systems.^[74] A German case study on storage of hydrogen in salt caverns found that if the German power surplus (7% of total variable renewable generation by 2025 and 20% by 2050) would be converted to hydrogen and stored underground, these quantities would require some 15 caverns of 500,000 cubic metres each by 2025 and some 60 caverns by 2050 – corresponding to approximately one third of the number of underground gas caverns currently operated in Germany.^[75] In the US, Sandia Labs are conducting research into the storage of hydrogen in depleted oil and gas fields, which could easily absorb large amounts of renewably produced hydrogen as there are some 2.7 million depleted wells in existence.^[76]

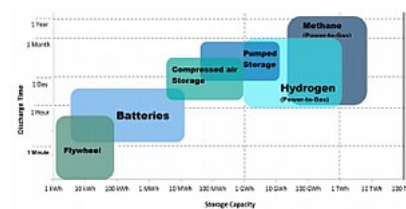


Figure 3. Available storage technologies, their capacity and discharge time. Source: School of Engineering, MIT University (2015)

'Available storage technologies, their capacity and discharge time.'
COMMISSION STAFF WORKING DOCUMENT Energy storage – the role of electricity

Power to gas

Power to gas is a technology which converts electrical power to a gas fuel. There are two methods: the first is to use the electricity for water splitting and inject the resulting hydrogen into the natural gas grid; the second, less efficient method is used to convert carbon dioxide and hydrogen to methane, (see natural gas) using electrolysis and the Sabatier reaction. A third option is to combine the hydrogen via electrolysis with a source of carbon (either carbon dioxide or carbon monoxide from biogas, from industrial processes or via direct air-captured carbon dioxide) via biomethanation,^{[77][78]} where biomethanogens (archaea) consume carbon dioxide and hydrogen and produce methane within an anaerobic environment. This process is highly efficient, as the archaea are self-replicating and only require low-grade (60°C) heat to perform the reaction.

Another process has also been achieved by SoCalGas to convert the carbon dioxide in raw biogas to methane in a single electrochemical step, representing a simpler method of converting excess renewable electricity into storable natural gas.^[79]

The UK has completed surveys and is preparing to start injecting hydrogen into the gas grid as the grid previously carried 'town gas' which is a 50% hydrogen-methane gas formed from coal. Auditors KPMG found that converting the UK to hydrogen gas could be £150bn to £200bn cheaper than rewiring British homes to use electric heating powered by lower-carbon sources.^[80]

Excess power or off peak power generated by wind generators or solar arrays can then be used for load balancing in the energy grid. Using the existing natural gas system for hydrogen, Fuel cell maker Hydrogenics and natural gas distributor Enbridge have teamed up to develop such a power to gas system in Canada.^[81]

Pipeline storage of hydrogen where a natural gas network is used for the storage of hydrogen. Before switching to natural gas, the German gas networks were operated using towngas, which for the most part (60-65%) consisted of hydrogen. The storage capacity of the German natural gas network is more than 200,000 GW·h which is enough for several months of energy requirement. By comparison, the capacity of all German pumped storage power plants amounts to only about 40 GW·h. The transport of energy through a gas network is done with much less loss (<0.1%) than in a power network (8%). The use of the existing natural gas pipelines for hydrogen was studied by NaturalHy^[82]

Automotive Onboard hydrogen storage

Storage Parameter	2005	2010	2015
Gravimetric Capacity (Specific energy)	1.5 kWh/kg 0.045 kg H ₂ /kg	2.0 kWh/kg 0.060 kg H ₂ /kg	3.0 kWh/kg 0.090 kg H ₂ /kg
System Weight:	111 Kg	83 Kg	55.6 Kg
Volumetric Capacity (Energy density)	1.2 kWh/L 0.036 kg H ₂ /L	1.5 kWh/L 0.045 kg H ₂ /L	2.7 kWh/L 0.081 kg H ₂ /L
System Volume:	139 L	111 L	62 L
Storage system cost	\$6 /kWh	\$4 /kWh	\$2 /kWh
System Cost:	\$1000	\$666	\$333
Refueling rate	.5 Kg H ₂ /min	1.5 Kg H ₂ /min	2.0 Kg H ₂ /min
Refueling Time:	10 min	3.3 min	2.5 min

Targets for on-board hydrogen storage assuming storage of 5 kg of hydrogen^[83]

Targets were set by the FreedomCAR Partnership in January 2002 between the United States Council for Automotive Research (USCAR) and U.S. DOE (Targets assume a 5-kg H₂ storage system). The 2005 targets were not reached in 2005.^[84] The targets were revised in 2009 to reflect new data on system efficiencies obtained from fleets of test cars.^[85] The ultimate goal for volumetric storage is still above the theoretical density of liquid hydrogen.^[86]

It is important to note that these targets are for the hydrogen storage system, not the hydrogen storage material. System densities are often around half those of the working material, thus while a material may store 6 wt% H₂, a working system using that material may only achieve 3 wt% when the weight of tanks, temperature and pressure control equipment, etc., is considered.

In 2010, only two storage technologies were identified as having the potential to meet DOE targets: MOF-177 exceeds 2010 target for volumetric capacity, while cryo-compressed H₂ exceeds more restrictive 2015 targets for both gravimetric and volumetric capacity (see slide 6 in ^[57]).

See also

- Cascade storage system
- Cryo-adsorption
- Hydrogenography
- Hydrogen energy plant in Denmark
- Industrial gas
- Tunable nanoporous carbon

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