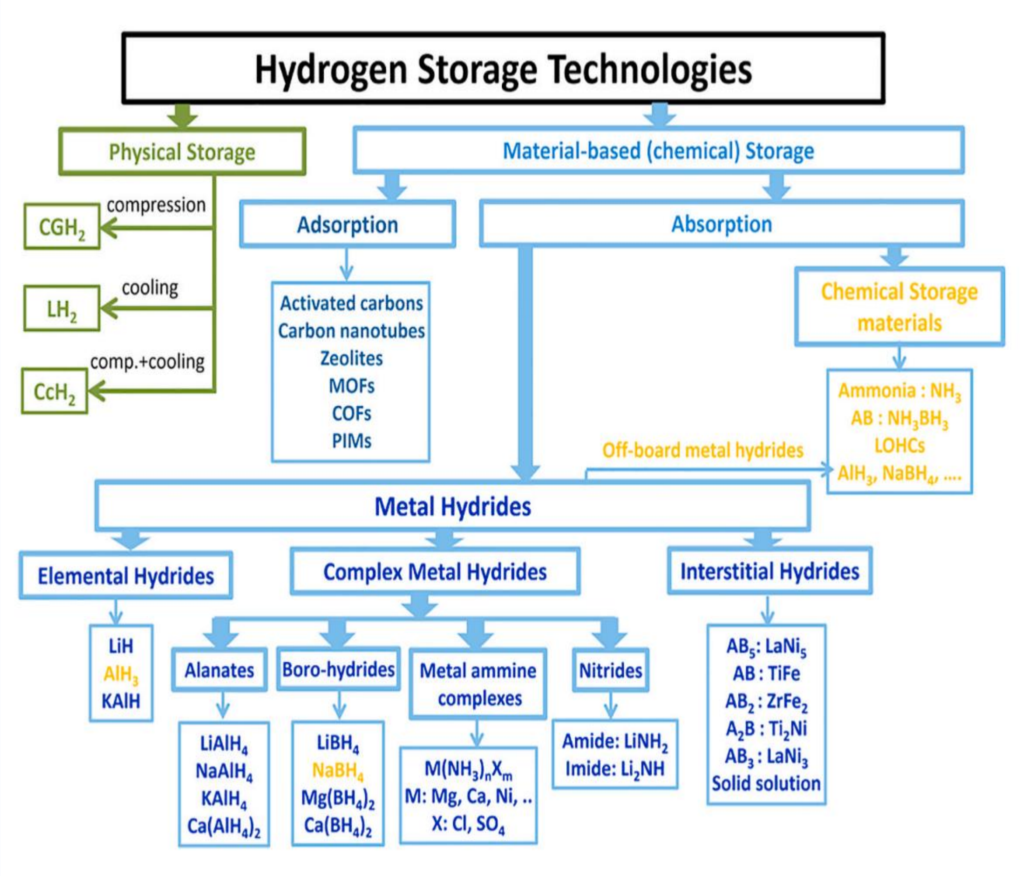
Compressed Hydrogen Storage Tanks

Presentation Outline

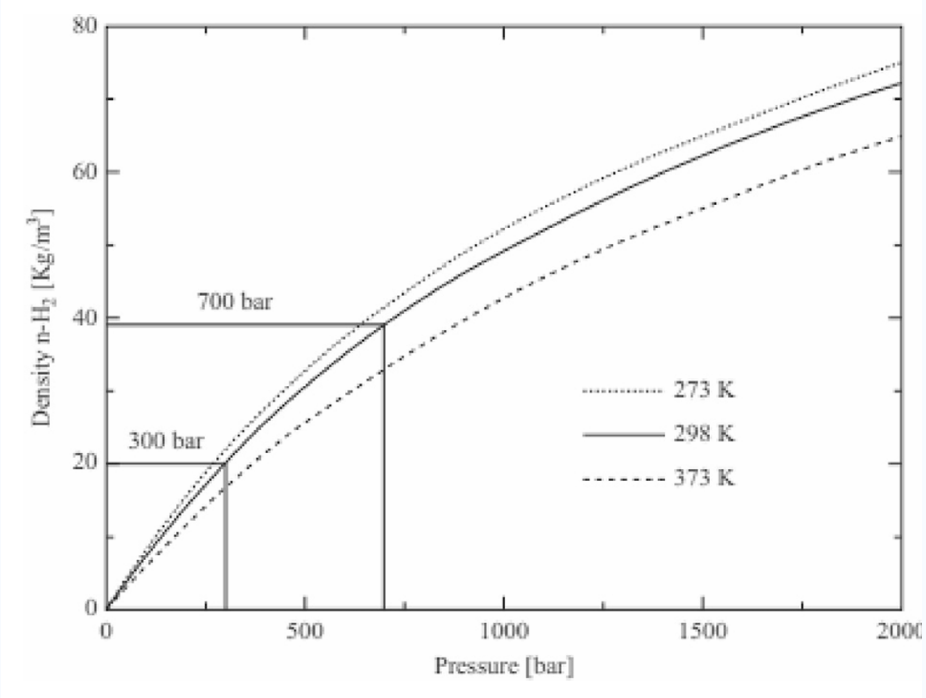
Compressed Gas Hydrogen Storage (CGH2)



I.A. Hassan et al., Renewable and Sustainable Energy Reviews 149 (2021) 111311

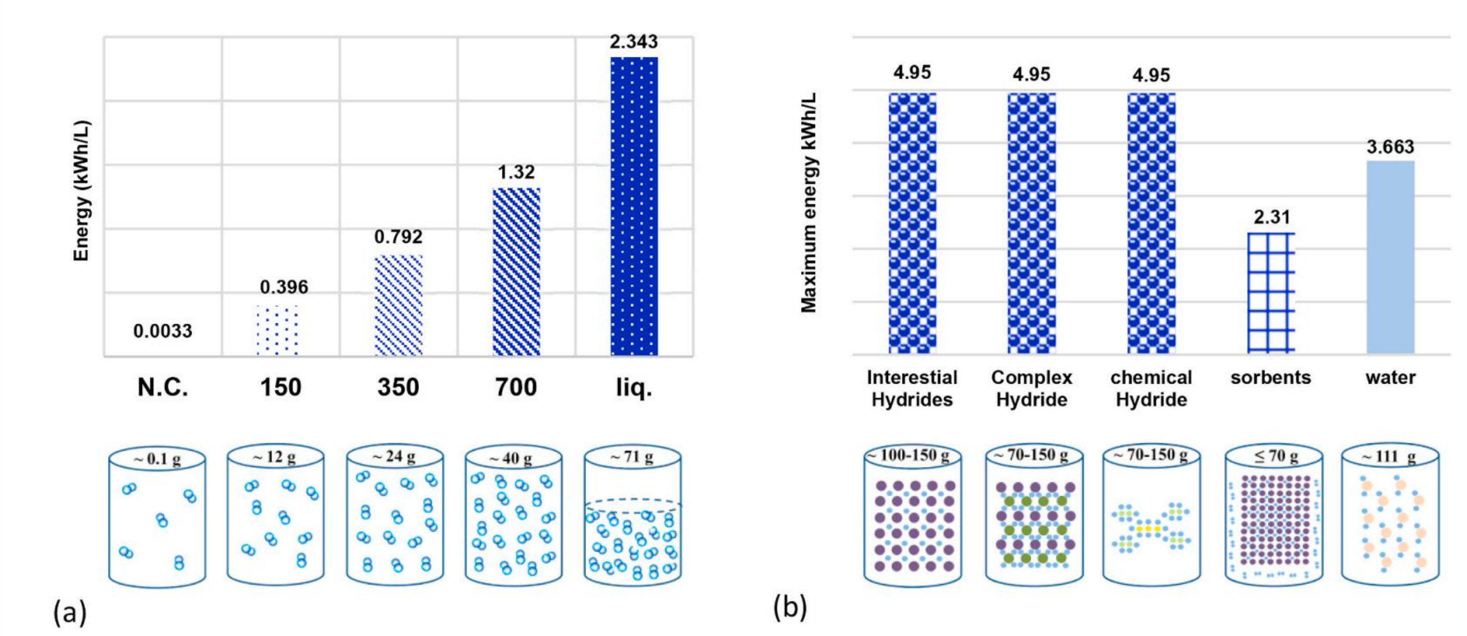
Pressure Effects on Hydrogen Density

- At normal temperature and pressure:
  hydrogen density = 0.08 kg/m³
- Compressed to 35 MPa:
  density increases to 23 kg/m³
- Compressed to 70 MPa:
  density increases to 38 kg/m³
- Higher pressure storage dramatically improves volumetric energy density
- This enables practical onboard storage for vehicle applications
- **Trade-off: increased pressure demands stronger, more sophisticated tank designs**



Omar Faye et al., IJHE, 2022

Hydrogen Density vs. Pressure



As pressure increases from 1 bar to 700 bar, the hydrogen density increases from 0.1 g/L to 40 g/L, and consequently energy volumetric density increases from 0.0033 kWh/L to 1.32 kWh/L respectively.

As rule of thumb to pressurize hydrogen to 700 bar, the consumed power is about 10% of the gas energy content.

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Tank Types Overview

Type			I	II	III	IV	V
Schematic							
Components and related failures	Metallic	part	Fully metallic	Metallic enclosure	Metallic liner	Boss	-
		Failure	- Hydrogen Embrittlement, mechanical properties degradation and premature cracks. - Premature failure for fatigue for metal liner and liner damage$^{\alpha}$. **Reason:** contact between metal and Hydrogen, surface impact$^{\alpha}$.				
	Composite	part	Not applicable	Some fibre over-wrap	Full composite over-wrap		Fully composite
		failure		Fibber breaks, delamination and matrix cracking, composite thickness decrease. **Reason :** accidental mechanical impacts and subsequent pressure loads.			
	Polymer	part	not applicable			Polymer liner	Under consideration
		failure				Permeation, leakage **Reason :** contact between polymer and H_2, charge/discharge conditions	
Pressure limit			≤ 50 MPa	Not limited	≤ 45 MPa	≤ 100 MPa	
Vessel price			++	+	-	-	
Gravimetric capacity wt. % or tank mass			-	±	+	++	
Popularity & maturity			****	**	*	*	

However, as pressure increases, safety issues arise.
Pressure vessels are divided into five types according to their components, which consequently control their characteristics.

Type-I Tanks: Steel Cylinders

Compressing hydrogen, which has an extremely low density of 0.083 kg/m³ at NTP, requires a tremendous amount of energy. Hydrogen is usually stored in steel cylinders up to a pressure of 200 bar — the most common hydrogen tanks used for general industrial applications.

With Type-I tanks, a gravimetric density of around 1% can be attained — meaning the weight of stored hydrogen is around 1% of the weight of the vessel itself. This low gravimetric efficiency makes Type-I unsuitable for mobile or space-constrained applications.

Gravimetric Density: ~1%

Max Pressure: 200 bar

Application: General Industrial

Source: https://www.sciencedirect.com/science/article/pii/S0360319923021584

Tank Types I & II

Type-I — Steel Cylinder

Suitable for industrial use where warehouses are readily available and the cost of sophisticated tank material and compressing hydrogen would exceed the cost of warehousing.

- All-metal construction
- Gravimetric capacity: ~1 wt%
- Working pressure: up to 200 bar
- Lowest cost option

Type-II — Hoop-Wrapped

Thick aluminium or steel liner wrapped with a fibre-resin composite mesh covering only the lateral (cylindrical) surface area. Enhances load-bearing capacity for higher pressures.

- Metal liner + composite hoop wrap
- Weight reduction: up to 40% vs Type-I
- Working pressure: up to 300 bar
- Cost: ~1.5× Type-I

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Tank Types III & IV

Type-III — Full-Wrapped Metal Liner

Full surface-area liner wrapped with composite. The composite outer shell bears ~95% of mechanical load; the metal liner acts mainly as a sealing agent.

- Metal liner + full composite wrap
- Allowable pressure: 350–700 bar
- Lighter than Types I & II
- Better fatigue and corrosion resistance

Type-IV — Full Composite / Polymer Liner

Carbon fibre composite overwrap with polymer (e.g. HDPE) liner. Ideal for mobile applications due to lightweight construction.

- Carbon fibre + polymer liner
- Toyota Mirai: 5.7 wt% gravimetric capacity
- Allowable pressure: up to 750 bar (700 bar typical)
- Best gravimetric performance; 5× Type-I

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Composite Pressure Vessels: Performance & Applications

For industrial applications, hydrogen is usually stored between 20 and 30 MPa in metallic Type-I cylinders of deficient gravimetric capacity (about 1 wt%).
Type-IV utilizes a polymer liner instead of metallic one and hence offers better gravimetric performance. After polymerization, the carbon fibre reinforced polymer (CFRP) possesses sufficient mechanical properties and works as the main load-bearing unit.

Composite filament wound technology could improve storage performance due to lightweight construction, high strength, and adequate resistance for both fatigue and corrosion. Gravimetric capacity of composite pressure vessels could exceed four times that of steel vessels working at the same pressure.

According to DOE targets for light duty vehicles (2020): 4.5 wt% and 0.030 kg-H_2/L.
Type-IV has achieved 4.2 wt% and 0.024 kg-H_2/L at 700 bar, enabling travel distances of more than 450 km with less than 3 min fuelling time.

Pressure vessels for vehicular applications are composed of four layers: aluminium alloy lined internally with plastic and covered externally by carbon fibres, with an outer fibre glass layer as shock absorber.

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LIQUID HYDROGEN STORAGE

Liquid Hydrogen (LH_2) Overview

70.9 kg/m³	20 K	~35%	71.0 kg/m³
LH_2 Storage Density	Required Temperature	Energy for Liquefaction	Density at 20 K / 0.4 MPa

Among hydrogen storage technologies, liquid hydrogen (LH_2) storage, requiring 20 K, is characterized by significant storage density of 70.9 kg-H_2/m³, as well as safety benefits with respect to high storage pressure. Total power consumption for LH_2 storage is about 35% of the energy content of the stored hydrogen, which is considerably more than other HST options. LH_2 is therefore limited to flight and space applications where high volumetric and gravimetric energy storage densities are required regardless of high power consumption.

Cryo-compressed Hydrogen (CcH_2) storage offers high volumetric and gravimetric capacity with less energy consumption.
Temperature and pressure ranges for most effective hydrogen storage are: 35–110 K and 5–70 MPa, corresponding to hydrogen densities of 60.0–71.5 kg/m³.

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Challenges in Liquid Hydrogen Storage

Boil-Off Loss & Pressure

Hydrogen has an ultra-low boiling point (20 K) — much lower than nitrogen (78 K) or oxygen (90 K). The temperature difference between ambient and the liquid storage tank is huge, causing constant evaporation.

NASA's Kennedy Space Center liquid hydrogen tank has boil-off losses at the rate of 2,000 L per day. A pressure relief valve must be employed to vent the hydrogen and prevent pressure build-up.

Energy-Intensive Liquefaction

Liquefaction of hydrogen is an energy-intensive process. A proper choice of liquefaction technique must be made based on design capacity and operating conditions.

The hydrogen that blows off is already at a lower temperature; this component might be handled carefully to save energy — for instance, evaporated hydrogen gas can either be re-liquefied or stored using metal hydrides.

Hassan et al., Renewable and Sustainable Energy Reviews 149 (2021) 111311

BOIL-OFF PROBLEM

What is Boil-Off Gas (BOG)?

Cryogenics is known as the science and technology of very low temperatures — below 120 K.
A major challenge in cryogenic process engineering is the minimization of the inherent heat transfer from the environment to the cryogenic fluid in a given storage tank.

A consequence of this heat input to the storage tank is the generally slow but continuous vaporization of the cryogenic liquid due to the low boiling point of the fluid. The new gas phase in the container is known as boil-off gas (BOG).

Key insight: H_2 has an enthalpy of evaporation of only 0.45 kJ/g — almost 18× lower than liquefied natural gas (LNG). This makes it extremely difficult to maintain in liquid state.

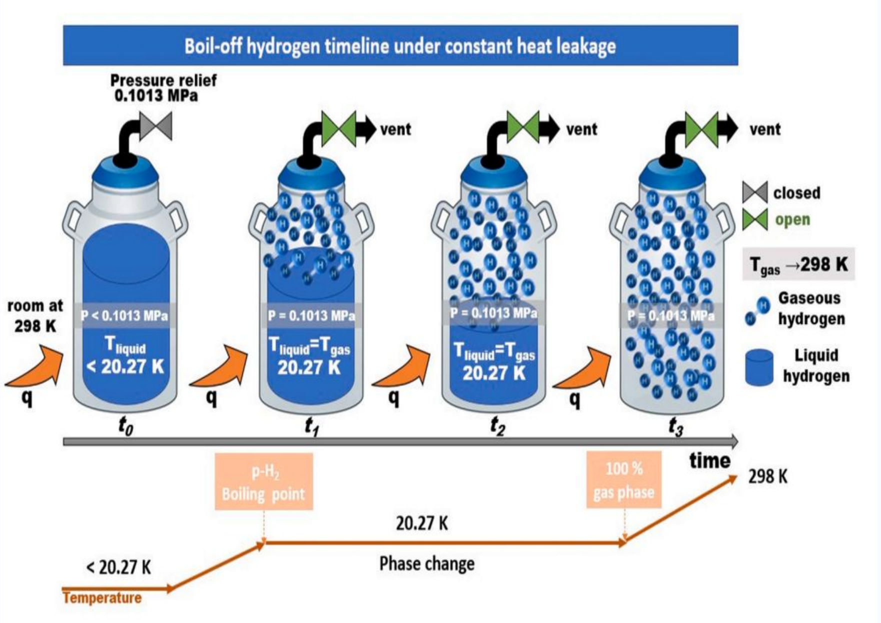
R. Morales-Ospino et al., Renewable and Sustainable Energy Reviews 182 (2023) 113360

Heat Leakage and BOH Formation Timeline

The sequential process of LH_2 boil-off under heat leakage:

- t_0: LH_2 stored at slightly below boiling point, tank at ~0.1 MPa
- $t_0 – t_1$: Heat overcomes tank insulation resistance
- t_1: LH_2 reaches boiling point (20.271 K), safety valve opens, H_2 boil-off begins
- t_2: LH_2 level decreases, BOH occupies vacated space
- t_3: All LH_2 has transformed to gas; temperature rises to ambient

Once the allowable tank pressure is reached, the pressure relief device activates to control the internal tank pressure.



Morales-Ospino et al., Renewable and Sustainable Energy Reviews 182 (2023) 113360

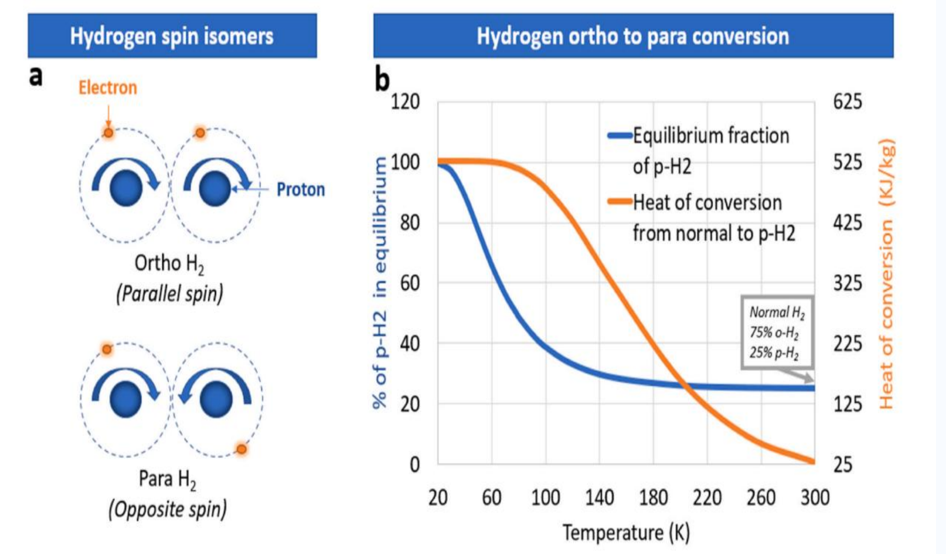
Causes of Boil-Off Hydrogen (BOH)

Ortho→Para H_2 Conversion: Normal H_2 (room temp): 75% ortho + 25% para. As temperature decreases, equilibrium shifts toward para-H_2. This spontaneous conversion can vaporize up to 64% of original LH_2. Catalysts (Fe_2O_3, $CrO{\cdot}SiO_2$) are used to accelerate conversion during liquefaction.

Heat Leaks: Conduction via pipes, access ports, supports; radiation through insulation. Shape and size effect: boil-off rate is proportional to surface-to-volume ratio.

Sloshing: Movement of LH_2 during transport; impact energy converts to thermal energy causing evaporation. Cross baffles inside the tank can mitigate impact forces.

Flashing: Quick vaporization when transferring LH_2 from high-pressure (0.24–0.27 MPa) to low-pressure Dewars (~0.12 MPa).



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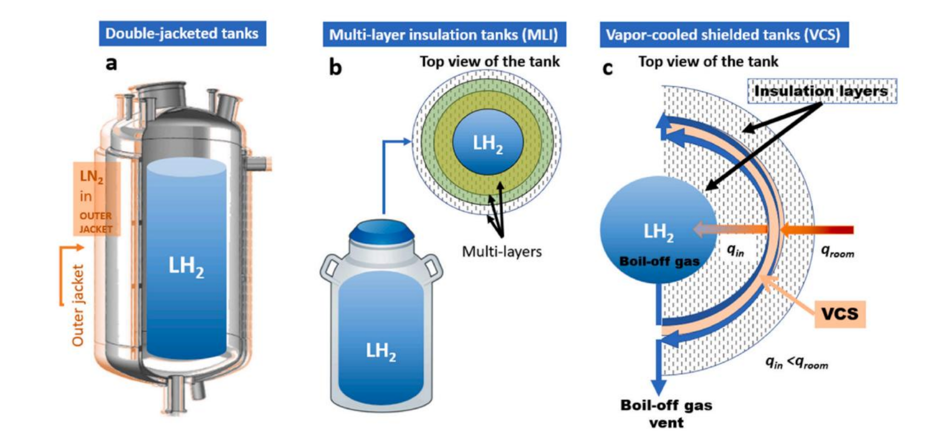
Boil-Off Rates and Tank Insulation

Boil-off losses are proportional to surface-to-volume ratio and decrease sharply as storage tank size increases:

- 50 m^3 spherical, vacuum-insulated Dewars: 0.3–0.5% per day
- 10^3 m^3 tanks: 0.2% per day
- 19,000 m^3 tanks: ~0.06% per day
- Most current LH_2 tanks: 0.3–3% per day



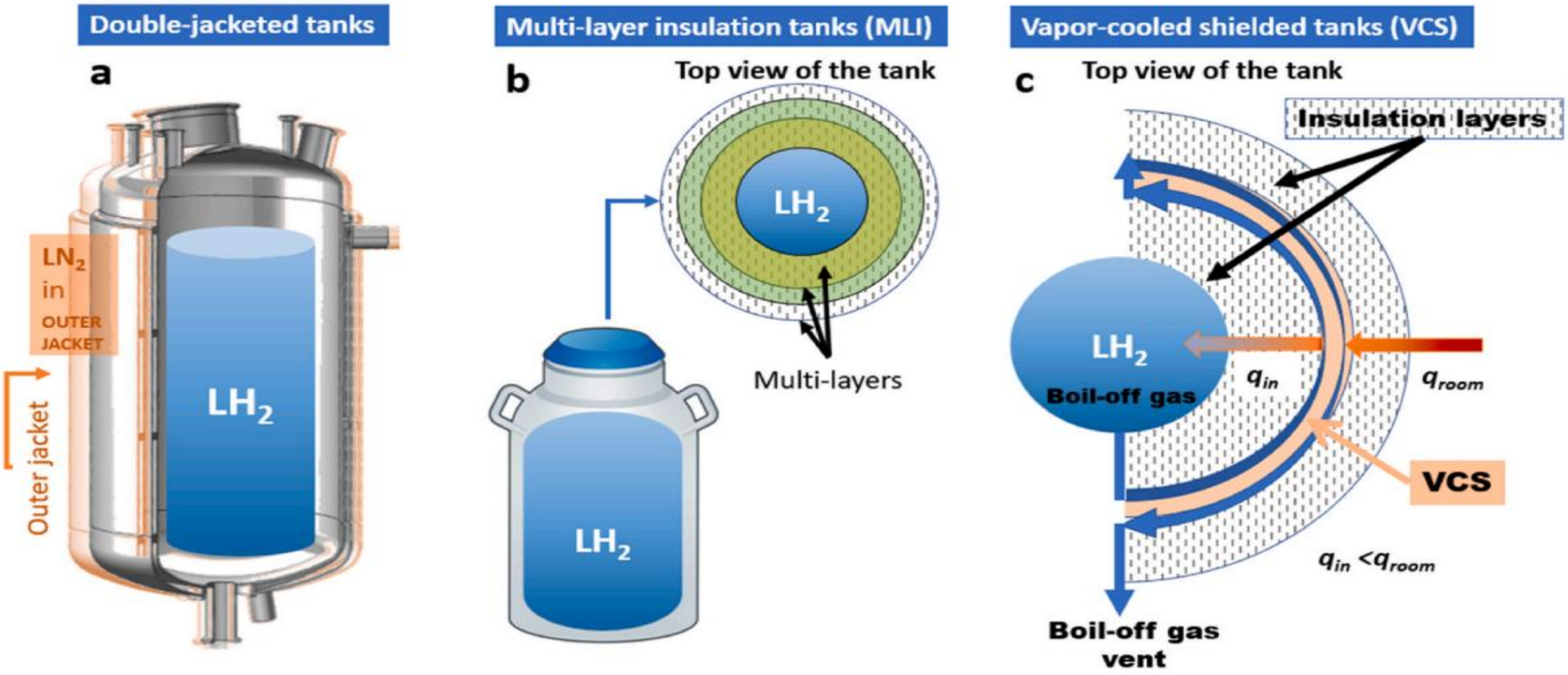
Three main tank types:

- Double-jacketed tanks with liquid nitrogen on outer jacket
- Super-insulated tanks with reflective powder or multi-layer insulation (MLI)
- Vapor-cooled shielded (VCS) tanks using super-insulation

MLI thermal conductivity: 10–50 µW/mK at 20–300 K (alternating aluminium foil / aluminized Mylar + fibreglass/paper under high vacuum).

Morales-Ospino et al., Renewable and Sustainable Energy Reviews 182 (2023) 113360

Insulation System Types for LH_2 Tanks



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Thermal Stratification, Sloshing, and Flashing

Thermal Stratification: Heat input through free convection causes warmer LH_2 to rise to the surface. Pressure corresponds to vapor pressure of the warmer upper layers. Solution: high-conductivity vertical plates in the tank, or magnetic-type refrigerators to maintain LH_2 in subcooled/saturated conditions.

Sloshing (During Transport): LH_2 movement due to acceleration/deceleration converts impact energy to thermal energy, causing evaporation. Cross baffles inside the tank mitigate impact forces.

Flashing: Quick vaporization during LH_2 transfer from high-pressure (0.24–0.27 MPa) to low-pressure Dewars (~0.12 MPa). Storing at lower pressures (near atmospheric) mitigates this, at the expense of smaller stored volume.

Vapor-Cooled Shields (VCS): Heat exchange between low-temperature BOH and incoming ambient heat can reduce heat leakage significantly. VCS optimization parameter β can reach up to 60.5% heat flux reduction.

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BOH Venting and Recovery Strategies

In many LH_2 storage/transport applications, the BOH is simply vented to the atmosphere to prevent overpressure. While this can be the simplest solution, venting is a waste of energy for a gas that is expensive to liquefy. Large amounts of BOH vented into confined spaces can become hazardous due to explosion risk.

Boil-off recovery strategies to consider:

Reliquefaction: Optimal for LH_2-fueled applications or transportation. Main drawback: need for additional adjacent space and relatively high OPEX and CAPEX of the cooling process.

Compression: Recovers H_2 in gaseous state for fuel cell vehicle refueling or high-pressure buffer storage. Recovery energy cost must not exceed the value of recovered BOH.

Zero Boil-Off (ZBO): Combines passive multi-layer insulation with active cryogenic cooling. Currently limited to spacecraft industry due to sophisticated requirements.

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ZERO BOIL-OFF & RELIQUEFACTION

Zero Boil-Off (ZBO) Concept

Since the 1960s, NASA has developed cryogenic refrigeration systems such as the 20 K cryocooler to achieve zero boil-off (ZBO) of LH_2 for long-duration space missions.

The ZBO storage system combines passive insulation technology (multilayer and cooled shield) with active cooling technology. A cryocooler removes the 'heat load' entering through the tank walls, maintaining the LH_2 at 20 K without venting BOH.

The reverse Brayton cycle remains the preferred distributed cooling system for ZBO. First ZBO proof-of-concept: NASA Glenn Research Center, 1998. Second test: NASA Marshall Space Flight Center, 2000.

20 K — LH_2 maintained at

~8 K — Thermal gradient challenge (1st test)

~90% — BOH reduction achieved for O_2/N_2

ZBO is currently limited to spacecraft applications due to size, weight, and complexity constraints. Open issues include increasing the lift rate while maintaining practical system dimensions.

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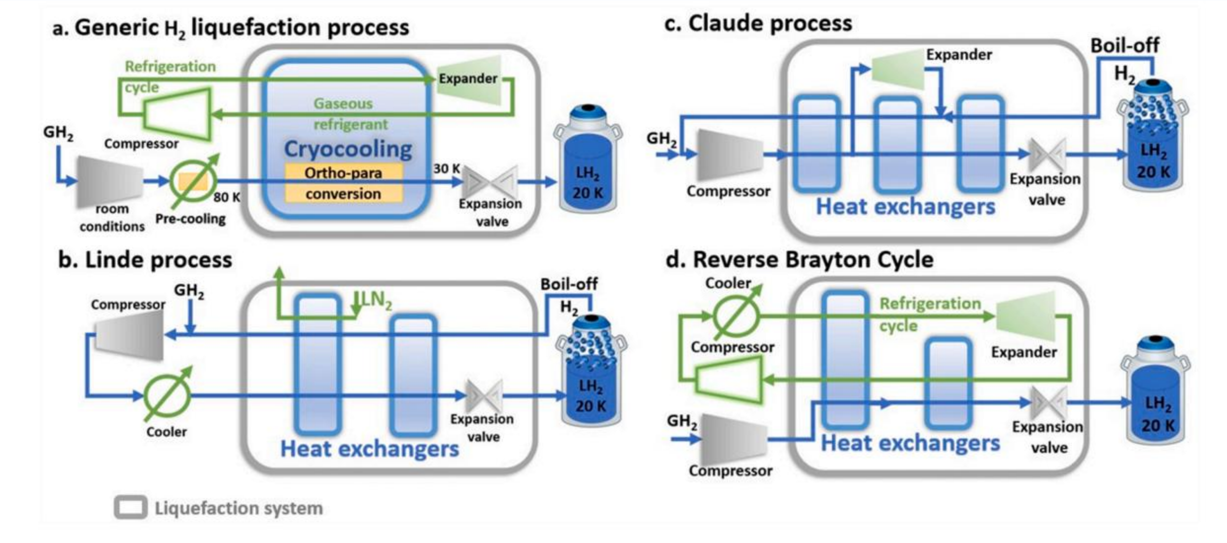
H_2 Liquefaction: Process Overview

Liquefaction of H_2 requires about 10× more energy than LNG (3.92 kWh/kg LH_2 vs 0.31 kWh/kg LNG). The process includes:

1. H_2 compression
2. Pre-cooling to ~80 K
3. Cryocooling to ~30 K (helium reverse Brayton or H_2 Claude cycle)
4. Joule-Thomson (J-T) expansion to 20 K at atmospheric pressure

Catalysts are used during both cooling steps to accelerate ortho-to-para H_2 conversion. Para-H_2 content after liquefaction: 95–98%. Specific Energy Consumption (SEC): 10–15 kWh/kg LH_2 for current plants; could drop to 5–8 kWh/kg for large-scale conceptual plants.



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CASE STUDY

NASA Kennedy Space Center

Large-scale liquid hydrogen storage for rocket propulsion

NASA Kennedy Space Center — LH_2 Storage

For decades, NASA has harnessed hydrogen fuel to power rockets. Each rocket carries over 2.65 million litres of liquid hydrogen. To meet this demand, KSC has two large-scale liquid hydrogen storage tanks.

Original Tank (1960s)

Capacity: 3.22M litres
Outer diameter: 21 m
Max working pressure: 6.2 bar
Insulation: evacuated perlite (~1,200 mm thick)
Boil-off: 0.0625% = 2,000 L/day

New Tank (as of 2018)

Capacity: 4.73M litres
Diameter: ~25.3 m, 15 support legs
Insulation: Glass Bubbles Thermal Insulation (GBTIS)
Boil-off: 0.048% = ~2,271 L/day
Reduction of boil-off rate vs original

Key Takeaways

Compressed gas storage (CGH2): Type-IV composite tanks at 700 bar enable 5× gravimetric density vs steel cylinders. Practical for mobile applications.

Liquid hydrogen (LH_2): 70.9 kg/m³ storage density but requires 20 K and ~35% of gas energy to liquefy. Best for aerospace/space.

Boil-off is unavoidable: Heat leakage, ortho→para conversion, sloshing and flashing all contribute. Multi-layer insulation + VCS can reduce to <0.1%/day for large tanks.

Zero Boil-Off: Combining passive MLI with active cryocooling eliminates venting. Currently limited to spacecraft industry.

Ductility at Very Low Temperatures

Hydrogen boils at approximately **−253 °C at atmospheric pressure**, meaning that storage vessels and related infrastructure must operate under extremely low temperatures.

At such conditions, materials must retain sufficient **ductility and toughness** to prevent brittle fracture that could compromise the structural integrity of the container.

Several **stainless steel grades** are widely used in these environments and are specified in technical standards such as the **ASME Boiler and Pressure Vessel Code** and **EN 13445-2**. These steels share a **stable austenitic microstructure**, which allows them to maintain mechanical toughness even at cryogenic temperatures, enabling safe operation down to about **−273 °C**.

Hydrogen Embrittlement under Pressure

- **Hydrogen embrittlement (HE)** is the loss of metal ductility caused by the absorption of hydrogen atoms, which can diffuse easily into metals and promote crack initiation and propagation.

- The susceptibility to HE depends on the **material type**: high-strength steels **Hydrogen embrittlement (HE)** is the loss of metal ductility caused by the absorption of hydrogen atoms, which can diffuse easily into metals and promote crack initiation and propagation.

- The and titanium alloys are particularly vulnerable, while stainless steels show different levels of resistance.

- The **risk increases with pressure**: below ~20 bar the risk is generally low, but at higher pressures hydrogen diffusion into the tank walls becomes more significant.

- **Austenitic stainless steels** are commonly used for hydrogen storage (200–300 bar) because hydrogen diffusion is more difficult compared with ferritic or martensitic steels.

Metal Hydrides for Hydrogen Storage: Principle

Metal hydrides (MH) store hydrogen through a **reversible chemical reaction** between hydrogen gas and a metal/alloy**.**
Hydrogen molecules dissociate on the metal surface and atomic hydrogen diffuses into the lattice, forming a metal hydride phase.

Storage process
•**Absorption (charging):** hydrogen is absorbed by the metal → hydride formation
•**Desorption (discharging):** hydrogen is released when temperature increases or pressure decreases

Advantages
•High **volumetric hydrogen density**
•Storage at **moderate pressures** (typically 1–50 bar)
•**Intrinsic safety** compared with compressed hydrogen

Types of Metal Hydride Materials

Different materials are used depending on the **operating temperature and pressure**.

1. **Intermetallic hydrides (low–moderate temperature)**

$LaNi_5$-based alloys (Lanthanum–Nickel**)**
TiFe alloys (Titanium-Iron**)**
ZrV_2 alloys (Zirconium–Vanadium**)**
Characteristics:
Good **reversibility**
Moderate storage capacity (~1–2 wt%)

2. Magnesium-based hydrides

•**MgH_2 (**Magnesium Hydride)
Characteristics:
•High theoretical capacity (~7.6 wt%)
•Abundant and low-cost
•Requires **high temperatures (~300–350°C)** for hydrogen release

Thermal Management

Thermal effects

Hydride reactions are strongly **thermodynamic-driven**:

•**Absorption is exothermic** → heat must be removed

•**Desorption is endothermic** → heat must be supplied