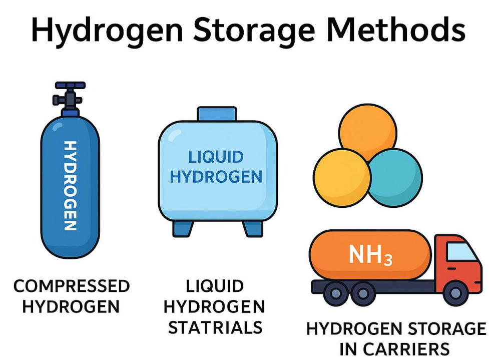
Hydrogen Storage and Infrastructure

Hydrogen storage is a critical component of the hydrogen economy, determining its feasibility for transport, power, and industrial applications. This lecture evaluates compressed hydrogen tanks, liquid hydrogen storage, and solid-state storage via metal hydrides and chemical carriers. Infrastructure and safety considerations are also discussed.

Hydrogen is characterized by high gravimetric energy density but very low volumetric density, making storage challenging. Different approaches to hydrogen storage are required depending on the application: vehicles, aerospace, stationary, or large-scale transport.



1. Compressed Hydrogen Tanks

Hydrogen gas can be compressed to 350–700 bar and stored in high-pressure tanks, typically made of carbon fiber composites. This is the dominant method in fuel cell vehicles such as the Toyota Mirai and Hyundai Nexo. Challenges include tank cost, weight, and safety at high pressures.

2. Liquid Hydrogen Storage

Hydrogen can be stored as a liquid at −253 °C. Cryogenic tanks are used, particularly in aerospace applications such as NASA rockets. While liquid hydrogen offers higher volumetric density, liquefaction consumes up to 30% of hydrogen's energy content. Boil-off losses and insulation requirements are further challenges.

3. Metal Hydrides and Chemical Storage

Metal hydrides, such as magnesium hydride (MgH_2) and lanthanum nickel hydride ($LaNi_5H_6$), can reversibly absorb hydrogen. Chemical carriers, such as ammonia (NH_3) and liquid organic hydrogen carriers (LOHCs), are also being developed. These methods offer safer, denser storage but face challenges of slow kinetics, regeneration energy requirements, and high weight.

Each hydrogen storage method has advantages and limitations: compressed gas is mature and suited for vehicles, liquid hydrogen is best for aerospace and large transport, and metal hydrides/chemical carriers may be most useful for stationary storage. Infrastructure development and safety assurance will be essential for scaling hydrogen technologies.

Table displayed the advantages and disadvantaged of different hydrogen storge

Storage Method	**Advantages**	**Disadvantages**
Compressed Hydrogen (High-pressure gas cylinders, 350–700 bar)	• Mature and widely used technology. • Relatively simple design and refueling. • Fast charging/discharging.	• Requires very high pressure → safety concerns. • Heavy, bulky tanks reduce energy density. • Expensive high-strength materials.
Liquid Hydrogen (Cryogenic, -253 °C)	• Higher energy density than compressed gas. • Useful for long-distance transport. • Suitable for aviation and space applications.	• Very high energy needed for liquefaction. • Boil-off losses due to evaporation. • Complex cryogenic storage system.
Solid-state / Material-based Storage (e.g., Metal hydrides, porous materials)	• Safe, low-pressure operation. • High volumetric density. • Potential for compact storage systems.	• Heavy materials reduce overall efficiency. • Slow absorption/desorption kinetics. • High cost of advanced materials.
Chemical Carriers (e.g., Ammonia, Methanol, LOHCs)	• Easier handling and transport using existing infrastructure. • High energy density. • Can be transported as liquid fuels.	• Requires energy-intensive conversion to release hydrogen. • Potential toxicity/safety issues (e.g., NH_3). • Adds complexity to fuel cycle.

6. Conclusion & Outlook

No single hydrogen storage method is universally optimal. A combination of compressed gas, liquid hydrogen, and solid-state storage will likely be deployed depending on the sector. Safe, cost-effective infrastructure is necessary to enable a global hydrogen economy.

References

[1] IEA. The Future of Hydrogen. 2019.

[2] Schlapbach, L.; Züttel, A. Hydrogen-Storage Materials for Mobile Applications. Nature, 2001.

[3] Barbir, F. PEM Fuel Cells: Theory and Practice. Elsevier, 2013.

[4] O'Hayre, R. Fuel Cell Fundamentals. Wiley, 2016.

Fuel Cell Performance and Efficiency

Fuel cells are promising electrochemical devices that convert chemical energy directly into electricity. Their efficiency and performance depend not only on thermodynamic limits but also on kinetic processes, mass transport, and operating conditions. Analyzing efficiency, polarization behavior, power density, and losses is critical for optimizing fuel cells for applications ranging from vehicles to stationary power plants.

1. Energy Conversion Efficiency

The theoretical efficiency of a hydrogen fuel cell is determined by the Gibbs free energy (ΔG) relative to the enthalpy (ΔH):

$\eta = \Delta G / \Delta H$

At 25 °C and 1 atm:
$\Delta H = -285.8$ kJ/mol, $\Delta G = -237.2$ kJ/mol → $\eta \approx 83\%$.

However, real cells achieve lower efficiency due to overpotentials. PEMFCs operate at 40–60%, SOFCs up to 65%. For comparison, internal combustion engines typically reach only ~30% efficiency.

Example: A 100 kW PEMFC stack delivering 55 kW electrical power with a fuel input of 120 kW (H_2 energy) yields:
$\eta = 55/120 \approx 45\%$.

Fuel Cell Efficiency – Detailed Math Problems with Step-by-Step Solutions

Problem 1 – Theoretical Efficiency (HHV vs. LHV)

Question:
The standard Gibbs free energy and enthalpy changes for the hydrogen–oxygen reaction forming liquid water at 25 °C are:
$\Delta G° = -237.13$ kJ/mol, $\Delta H° = -285.83$ kJ/mol.
For gaseous water (LHV basis): $\Delta G° = -228.6$ kJ/mol, $\Delta H° = -241.8$ kJ/mol.
1. Calculate the maximum (theoretical) efficiency on the HHV basis.
2. Calculate the maximum efficiency on the LHV basis.

Solution:
$\eta_{th} = \Delta G / \Delta H$
- HHV basis: $\eta = 237.13 / 285.83 = 0.8296 = 82.96\%$
- LHV basis: $\eta = 228.6 / 241.8 = 0.9449 = 94.49\%$

Final Answer:
HHV efficiency = 82.96%, LHV efficiency = 94.49%

Problem 2 – Efficiency at Given Voltage

Question:
A hydrogen fuel cell operates at 0.75 V. The reversible voltage is 1.229 V. The theoretical maximum efficiency on the HHV basis is 82.96%. Calculate the actual efficiency of the cell.

Solution:
$\eta = (V / E_{rev}) \times (\Delta G / \Delta H)$
$\eta = (0.75 / 1.229) \times 0.8296 = 0.6099 \times 0.8296 = 0.506 = 50.6\%$

Final Answer:
Cell efficiency = 50.6%

Problem 3 – Efficiency with Fuel Utilization

Question:
From Problem 2, the fuel cell has an efficiency of 50.6%. If the fuel utilization is 80%, calculate the overall fuel-to-electricity efficiency.

Solution:
$\eta_{overall} = u \times \eta_{cell} = 0.80 \times 0.506 = 0.405 = 40.5\%$

Final Answer:
Overall efficiency = 40.5%

Problem 4 – Net System Efficiency with Parasitic Loads

Question:
A stack delivers 5.0 kW DC output but consumes 0.6 kW for pumps and compressors. The fuel energy input is 11.5 kW (HHV basis). Calculate the net system efficiency.

Solution:
$P_{net} = 5.0 - 0.6 = 4.4$ kW
$\eta_{sys} = 4.4 / 11.5 = 0.383 = 38.3\%$

Final Answer:
System efficiency = 38.3%