

- SOEC: High-temperature operation using steam; can reduce electrical demand per kg H₂ when heat is available; earlier commercial maturity.

3) Thermodynamics, Energy & Water Needs

Illustrative system electricity draw: $\approx 52\text{--}55$ kWh per kg H₂ for AEL/PEM. Stack water need ≈ 9 L per kg H₂ (pretreatment/upstream water may increase total).

Rule-of-thumb design notes:

- Power price and utilization (capacity factor) dominate levelized cost of hydrogen (LCOH).
- PEM excels for fast load-following; pairing with variable renewables is common.
- SOEC benefits when high-grade heat or steam is already available.

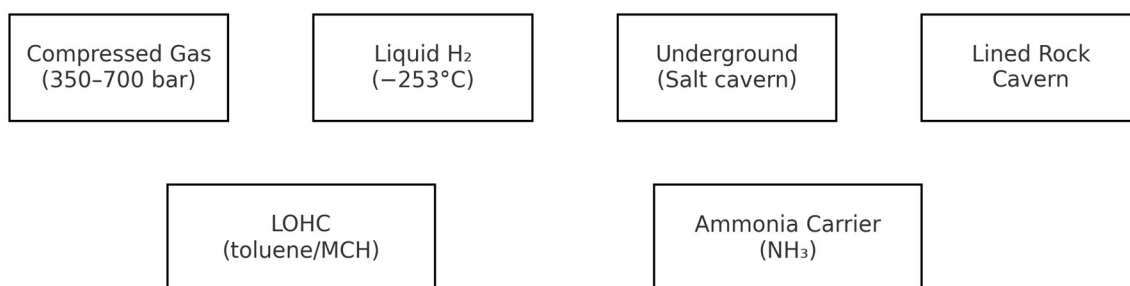
4) System Integration with Renewables

Electrolysers can act as flexible loads, absorbing surplus wind/solar and reducing curtailment. Storage decouples production from demand, enabling steady downstream processes.

5) Storage Pathways & Logistics

Options include compressed gas, liquid hydrogen, underground caverns, LOHC, and ammonia as a carrier. Choice depends on scale, distance, and end use.

Figure 2. Storage options overview.



6) Industrial Applications

1. Chemicals (near-term):
 - Ammonia (NH₃): Direct replacement of grey H₂ in Haber-Bosch; major potential volumes.
 - Methanol (CH₃OH): Synthesized from H₂ + CO₂; a platform for chemicals/e-fuels.
 - Refining: Hydrotreating/hydrocracking can substitute green H₂ for conventional hydrogen.

Figure 3. Green ammonia chain.

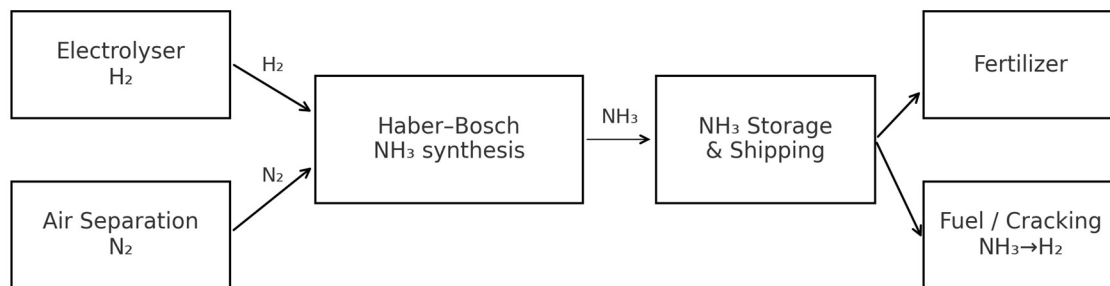
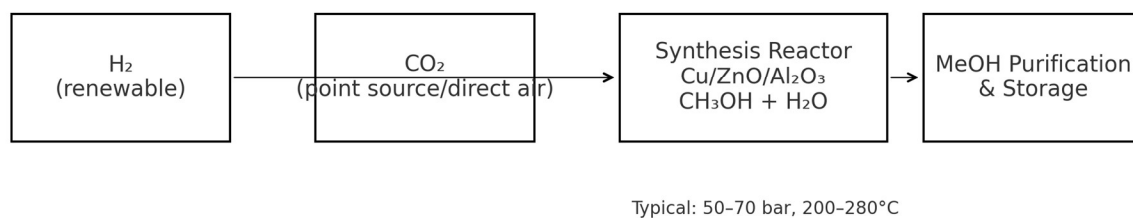


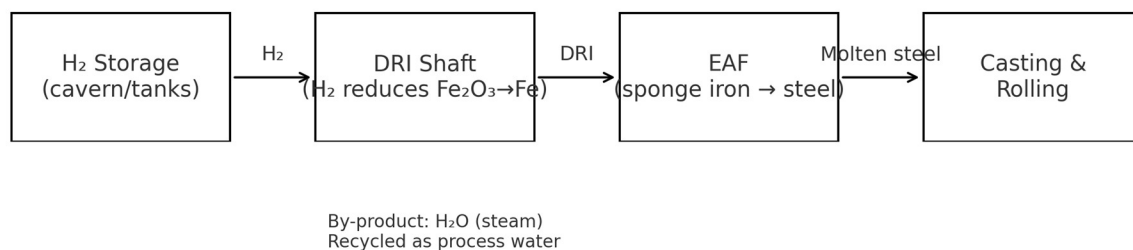
Figure 4. CO₂-to-methanol via green H₂.



2. Iron & Steel (H₂-DRI → EAF):

Hydrogen reduces iron ore to sponge iron in a shaft furnace; electric arc furnace melts and refines to steel. Early commercial projects are underway in Europe.

Figure 5. H₂-DRI to EAF steel flow.



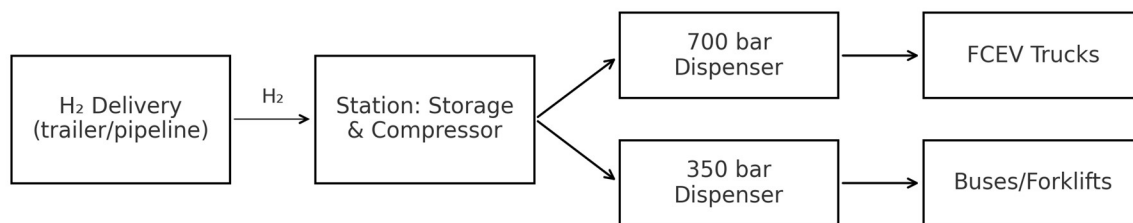
3. High-Temperature Process Heat:

Sectors like glass, ceramics, and chemicals may use H_2 where $>1000^\circ C$ heat is required and direct electrification is difficult.

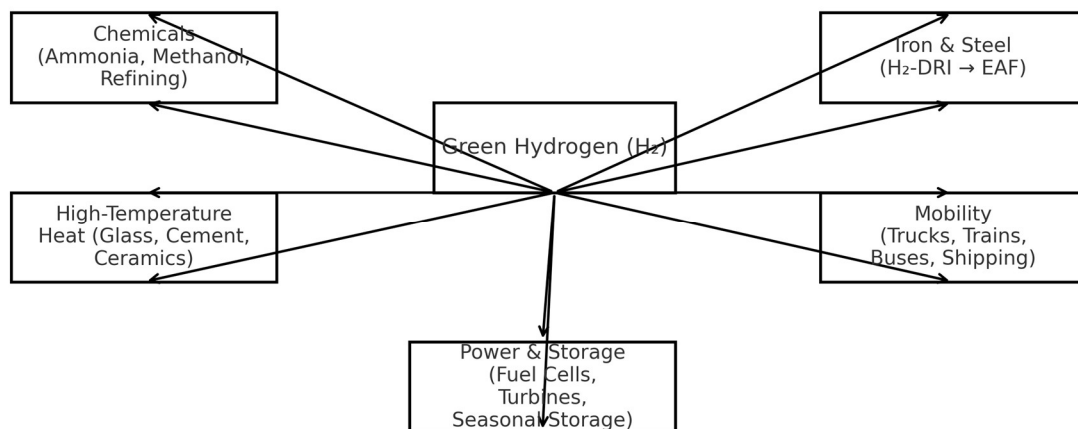
4. Mobility & Logistics:

Hydrogen refuelling for heavy-duty trucks, buses, trains, and port equipment; fuel-cell vehicles where fast refuelling/long range matter.

Figure 6. Station layout for mobility.



Industrial Applications of Green Hydrogen



7) Case Studies

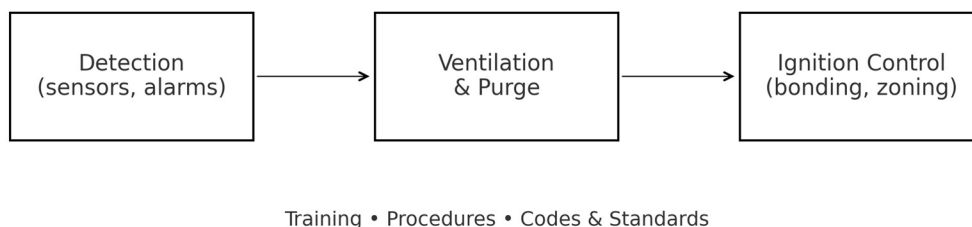
- HYBRIT (Sweden): hydrogen storage in rock caverns enables flexible steelmaking; DRI→EAF route demonstrates deep decarbonization.
- NEOM (Saudi Arabia): multi-GW renewables to green ammonia for export; illustrates mega-project integration.

- Oman Hydrom: structured land auctions and export orientation showcase policy-driven scaling.

8) Safety & Standards

Key pillars: detection, ventilation/purge, ignition control; plus training, procedures, and compliance with evolving codes/standards.

Figure 7. Safety building blocks.



9) Economics & Policy (LCOH Sensitivity)

Illustrative calculation (not a quote): If electricity costs \$20/MWh (\$0.02/kWh) and specific use is 52 kWh/kg, power cost \approx \$1.04/kg. At \$40/MWh, \approx \$2.08/kg. Add capex/opex proxies and consider incentives (e.g., U.S. 45V) to discuss net cost.

Appendix: Chemical Structures & Formulas (Educational)

- Hydrogen: H-H (σ bond); diatomic gas.
- Ammonia: NH_3 (trigonal pyramidal; H-N-H $\approx 107^\circ$).
- Methanol: $\text{CH}_3\text{-OH}$ (polar protic solvent; industrial intermediate).
- Methylcyclohexane (MCH) \leftrightarrow Toluene + 3H_2 (LOHC pair)