EFCH$_2$ 2025
European Fuel Cells and Hydrogen
PIERO LUNGHI CONFERENCE
September 17th-19th 2025
Capri / Italy

Techno-Economic Analysis of Hydrogen Storage Technologies for Different Real End-Use Demand Profiles and Sites

Andrea Ademollo*[a], Mattia Calabrese[a], Carlo Carcasci[a], Maurizio Vaccaro[b], Joshi Ipsita[b]

* Corresponding author: andrea.ademollo@unifi.it
[a] Università degli Studi di Firenze, Department of Industrial Engineering - DIEF, Via di Santa Marta 3, 50139 Firenze, Italy
[b] Baker Hughes – CTS, Via Felice Matteucci 2, 50127, Firenze (FI)

Keywords: hydrogen storage, metal hydrides, levelized cost of hydrogen

Abstract

This work presents a techno-economic analysis of hydrogen storage options—compressed tanks (Type I–IV), Underground Hydrogen Storage (UHS), and Metal Hydrides (MH)—for industrial and Hydrogen Refueling Station (HRS) demand profiles at diverse locations, subject to green-hydrogen emission limits. Hydrogen is generated from renewables (PV + wind) or grid power (if allowed), under site-specific electricity prices and carbon intensities. Different options were compared in terms of Levelized Cost of Hydrogen (LCOH), footprint, and GHG emissions. MH configurations address process heat integration via waste-heat recovery, electric heaters, or natural gas boilers—with or without Phase-Change Materials (PCM).
The resulting LCOH and Levelized Cost of Storage (LCOS) were evaluated, highlighting not only economic competitiveness but also the footprint and weight of the investigated storage solutions. Our findings show that: (i) hybrid off-grid systems (photovoltaic + wind) generally outperform single renewable energy source technology, (ii) UHS offers great advantages where high electricity prices are present, and (iii) for metal hydrides, leveraging on-site waste heat —as well as PCM adoption— reduces external energy needs and leads to competitive hydrogen production costs.

Introduction: *Green hydrogen deployment hinges on cost-competitive, scalable storage. While 700 bar compressed tanks are established, large-scale use demands lower-cost or higher-density solutions such as Underground Hydrogen Storage (UHS) or Metal Hydrides (MH). Likewise, each storage technology interacts differently with site constraints (grid emission intensity, renewable generation potential) and end-use demand (constant industrial load vs. fluctuating Hydrogen Refueling Station (HRS) profile) [1, 2].*
Metal hydrides (e.g., MgH_2) offer high volumetric density but need 200–350 °C heat for release. Integrating phase-change materials (PCM) in MH beds stores reaction heat, cutting external heat requirements [3, 4]. However, techno-economic trade-offs under real demand profiles and varied electricity/carbon costs remain underexplored.

Objectives:

- *Compare hydrogen storage technologies (compressed tanks, UHS, and MH) for two prototypical demand profiles (industrial vs. HRS) and identify the best-performing configurations by balancing capital cost, operational cost, and emissions compliance.*
- *Quantify how geography, renewable energy availability, grid carbon factors, and emissions thresholds affect the Levelized Cost of Hydrogen (LCOH).*
- *Assess MH systems' performance under different heat-supply scenarios (waste-heat reuse, electric boiler, natural gas boiler) and with or without PCM.*

Material and methods: *A Linear Programming optimization model has been developed to optimize the sizing of key components (PV, wind, electrolyzer, compressor and storage) as well as the hourly operation of the plant by minimizing LCOH over a 20-year horizon.*
Four representative sites—Bari (Italy), Bremen (Germany), Houston (USA), and Hajira (India)—were selected to capture varied conditions of renewable availability, grid electricity prices, and GHG limits. Two demand profiles —Industry: A constant 38 kg/h of hydrogen load at low delivery pressure (1 bar) and HRS: The same annual mean demand but exhibiting hourly peaks up to 85 kg/h and requiring final pressures up to 700 bar— were modelled in both off-grid (purely renewable) and grid-connected electrolyzer configurations. The latter one is subjected to location-specific GHG emission limits for green hydrogen certification.
Technical and economic data for PV, wind turbines, electrolyzers, compressors, tanks (Type I–IV, 30–700 bar), UHS, MH and PCM were drawn from literature and vendor information. MH systems were tested with six sub-variants, depending on the heat source (waste heat, electric boiler, or natural gas boiler) and on the presence of PCM to reduce external heat demand.

Results: *Industrial and HRS demand profiles gave similar results as the seasonality of HRS load profile —which is the one driving the storage size— is not really marked. The HRS experiences slightly higher LCOH because of extra compression requirements (up to 350–700 bar).*
In off-grid scenarios, a PV-wind hybrid typically outperformed single-source approaches by smoothing generation fluctuations, leading to lower overall LCOH. When grid electricity is available, cheap electricity purchase price (as in Hajira) combined with higher GHG thresholds greatly reduced system sizes and costs. In contrast, higher electricity prices (Bari, Bremen) often favoured enlarging hydrogen storage —especially if low-cost UHS is available— over purchasing electricity from the grid. The lowest LCOH (7,61€/kg) is obtained with UHS operating at 100 bar in Hajira in the grid-connected scenario when covering an industrial constant load profile (Figure 1), while the highest LCOH (12,36€/kg) is obtained with Tank Type IV operating at 700 bar in Houston in the off-grid scenario when covering the HRS load.
MH such as MgH_2-based systems proved economically advantageous whenever waste heat was readily available at sufficient temperature (300 °C) outperforming conventional tanks in

final LCOH (7,65€/kg) because of the absence of the compressor to reach extra-pressure or satisfy high pressure process needs, despite having a slightly higher storage CAPEX. Where no suitable heat source was present, a natural gas boiler or an electric boiler was required. Although that increased operational costs, the resulting LCOH still remained competitive in sites with low gas prices (Hajira and Houston). Integrating PCM reduce the external heat demand by 70%, but at the expense of higher storage CAPEX leading to a cost-effective adoption in case an electric heater is employed but not if a gas boiler is employed.

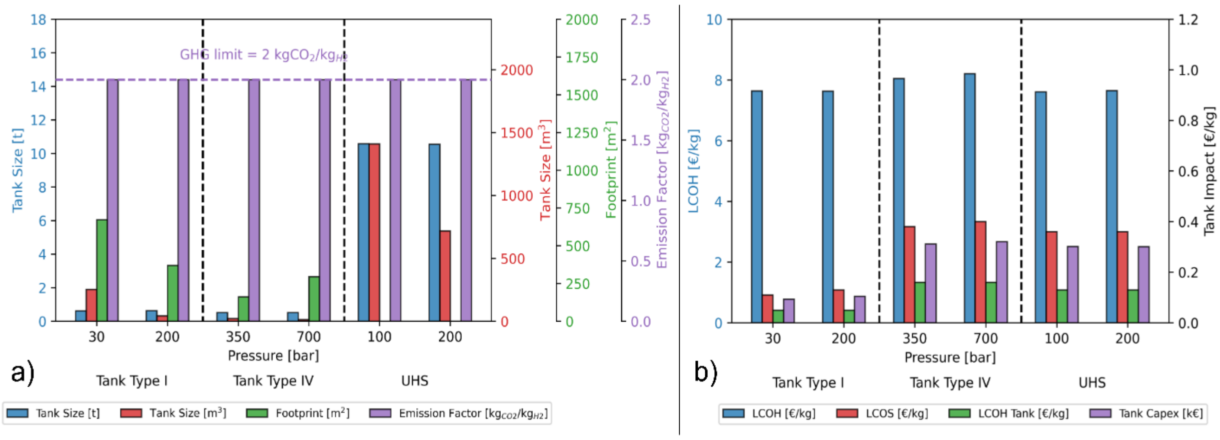

***Figure 1**: Optimal grid-connected PtH plant in Hajira (India) with different storage options for multiple pressure levels to satisfy a constant industrial hydrogen demand. a) Optimal storage configuration; b) Optimal economic KPIs.*

Conclusions: *This study demonstrates that no single hydrogen storage technology is universally optimal; rather, the best choice depends strongly on local renewable resources, electricity pricing, demand profile, and available heat sources and footprint requirements.*

References

[1] G. Karayel et al. “A comprehensive assessment of energy storage options for green hydrogen”. Energy Conversion and Management 2023.
[2] M. Yang et al. “A Review of Hydrogen Storage and Transport Technologies”. Clean Energy, 2023.
[3] Mellouli, M. et al. “Numerical analysis of metal hydride tank with phase change material.” Int. J. Hydr. Energy 2015.
[4] Garrier, S. et al. “A new MgH_2 tank concept using a phase-change material to store the heat of reaction.” Int. J. Hydr. Energy 2013.