catalysts

MDPI

Editorial

Catalysis for Hydrogen Storage and Release

Marco Martino [1,*], Valentina Naticchioni [2] and Giovanni Di Ilio [3]

[1] Hydrogen and New Vectors Laboratory (TERIN-DEC-H2V), Energy Technology and Renewable Sources Department, ENEA Portici Research Center, Piazzale Enrico Fermi, 1, Località Granatello, 80055 Portici, Italy
[2] Hydrogen and New Vectors Laboratory (TERIN-DEC-H2V), Energy Technology and Renewable Sources Department, ENEA Casaccia Research Center, via Anguillarese, 301, 00123 Rome, Italy; valentina.naticchioni@enea.it
[3] Engineering Department, University of Naples "Parthenope", Centro Direzionale, Isola C4, 80143 Naples, Italy; giovanni.diilio@uniparthenope.it
* Correspondence: marco.martino@enea.it

This editorial belongs the Special Issue titled "Catalysis for Hydrogen Storage and Release," which offers an updated overview of recent advances in hydrogen technologies based on the collected articles. Catalysis will remain a key enabling technology for building a competitive hydrogen economy. Beyond improving reaction kinetics, future catalytic systems must simultaneously address efficiency, durability, scalability, and economic sustainability under realistic operating conditions.

Understanding the drivers of climate change, a phenomenon underway for decades, remains a pressing global challenge. As early as the 1980s, U.S climate scientists warned that greenhouse gas emissions from fossil fuel combustion would destabilize the global climate system, triggering extreme weather events and environmental disasters. These early warnings went largely unheeded; today, atmospheric carbon dioxide concentrations have reached unprecedented levels, unseen in at least the last 800,000 years [1]. To mitigate these impacts, transitioning from fossil fuels to clean, renewable energy sources, the so-called "energy transition," is essential. This transition relies on three fundamental pillars: deep decarbonization, enhanced energy efficiency, and the deployment of green energy carriers. While direct electrification is widely regarded as the primary pathway toward decarbonization, it faces critical technical limitations in specific sectors [2]. Energy-intensive applications, such as heavy industry (e.g., metallurgy, chemical manufacturing) and long-haul transportation (shipping, aviation, and heavy-duty trucking), cannot be efficiently electrified due to the prohibitive weight and volume of current battery technology. Furthermore, grid-scale energy storage based on batteries remains constrained by low power and energy densities, high costs, and limited operational lifespans [3]. This presents a major bottleneck given the inherent intermittency of renewable sources, which necessitates energy carriers capable of long-duration, high-capacity storage [4]. Nowadays, hydrogen emerges as a paramount complementary energy carrier to electricity [5].

However, despite the remarkable scientific progress achieved over the last decade, significant barriers still prevent hydrogen technologies from reaching widespread industrial deployment. These include catalyst durability, process efficiency, critical raw materials, and the absence of harmonized technological pathways across different hydrogen value chains.

Hydrogen has an exceptionally high gravimetric energy density, high versatility, and the ability to be utilized in both thermal and electrochemical systems generating power with water as the sole byproduct. Additionally, it can serve as a feedstock for synthetic fuels (e-fuels), further expanding its decarbonization potential. Despite its promise, hydrogen production remains carbon-intensive: as of 2022, over 96% of Europe's hydrogen was

Check for updates

Received: 31 July 2026
Accepted: 5 August 2026
Published: 19 August 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

derived from natural gas steam reforming, resulting in substantial CO_2 emissions [6]. The widespread adoption of "green hydrogen" [7] is currently hampered by high production costs and the lack of efficient infrastructure for its transport and storage. Among the technological challenges associated with hydrogen production, storage, and utilization, catalysis represents perhaps the most influential scientific discipline, directly determining reaction efficiency, selectivity, process economics, and ultimately industrial feasibility.

The contributions collected in this Special Issue clearly illustrate the breadth of current catalytic research, spanning hydrogen production, purification, storage, and catalyst design. Together, they provide a comprehensive picture of how catalysis is evolving to address different stages of the hydrogen value chain.

In this context, photocatalytic hydrogen production represents an attractive approach; however, its large-scale deployment remains constrained by low solar conversion efficiencies, poor material stability, and high costs. To address these challenges, performance enhancements can be achieved by designing novel ternary semiconductor architectures, such as the g-C_3N_4/CoO/CoP system (Contribution 2). Such advances highlight how rational catalyst engineering is progressively moving from empirical optimization toward materials designed according to fundamental structure–property relationships.

Although fossil fuel-based production methods remain predominant, several strategies are being developed to mitigate their environmental impact. One prominent approach involves carbon capture and storage (CCS) integrated directly into the production line to intensify the process. A prime example is sorption-enhanced steam methane reforming (Contribution 3), where in situ CO_2 capture shifts the thermodynamic equilibrium forward while simultaneously sequestering greenhouse gases. Such approaches exemplify the growing trend toward process intensification, where catalysis and reactor engineering evolve synergistically. Among traditional processes, dry reforming of methane (DRM) plays a pivotal role by utilizing two greenhouse gases, methane and carbon dioxide, as feedstocks. While cost effective Ni-based catalysts are typically employed, they require high activation energies and operating temperatures, which lead to severe catalyst sintering and coke deactivation. To optimize these systems, various tuning strategies are being explored; for instance, nitrogen-doped carbon nanotubes can act as structural stabilizers for supported Ni nanoparticles (Contribution 1). The steam reforming of ethanol offers a sustainable pathway to bio-hydrogen, yielding up to six moles of H_2 per mole of reactant. Ethanol serves as an efficient hydrogen carrier with high gravimetric and volumetric energy densities. Recent developments show that doping ceria-supported Ni catalysts with Sm_2O_3 significantly evolves and enhances current catalytic systems (Contribution 5). Downstream production, hydrogen purity is crucial for the supply chain, particularly for proton-exchange membrane fuel cells (PEMFCs), which strictly require CO concentrations below 5 ppm. Achieving this purity necessitates highly selective catalysts for catalytic oxidation. Perovskite-type structures based on Co- and Ni-doped ceria exhibit promising catalytic behavior; modulating the ratio of these two metals activates distinct reaction mechanisms, offering a tailored pathway to engineer high-efficiency catalysts (Contribution 6).

Storing hydrogen efficiently is particularly challenging. Although hydrogen is the lightest element in the universe, its gaseous state under ambient conditions exhibits very low volumetric energy density, requiring energy-intensive compression or liquefaction. Chemical storage presents a viable alternative, leveraging liquid organic hydrogen carriers (LOHCs) or solid-state sorbents such as metal [8] and non-metal hydrides [9].

In this context, ammonia is gaining traction as a carbon-free hydrogen carrier due to its outstanding volumetric hydrogen density and ease of liquefaction. The increasing attention devoted to ammonia also reflects a broader shift toward integrated hydrogen carrier strategies, where storage, transportation, and utilization are considered simultane-

ously rather than as independent technological challenges. However, both its synthesis and decomposition are highly energy intensive, reducing overall process efficiency. Recent studies on alumina-supported iron catalysts for ammonia decomposition demonstrate highly competitive performances, identifying Fe_2O_3 as the primary active phase (Contribution 4).

The contributions collected in this Special Issue demonstrate that catalysis continues to be one of the primary scientific drivers enabling the hydrogen economy. While significant advances have been achieved across hydrogen production, purification, storage, and utilization, substantial challenges remain before these technologies can be translated into large-scale industrial applications. Future research should increasingly focus on catalyst durability, process integration, scalability, and standardized performance evaluation under realistic operating conditions.

Ultimately, the success of the hydrogen economy will depend not only on scientific discoveries but also on our ability to translate catalytic innovation into reliable, scalable, and economically viable technologies.

Author Contributions: Conceptualization, M.M., V.N. and G.D.I.; methodology, M.M.; investigation, M.M., V.N. and G.D.I.; resources, M.M., V.N. and G.D.I.; data curation, M.M., V.N. and G.D.I.; writing—original draft preparation, M.M., V.N. and G.D.I.; writing—review and editing, M.M., V.N. and G.D.I.; visualization, M.M., V.N. and G.D.I.; supervision, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Tao, Z.; Shen, D.; Liu, Y.; Zhang, X.; Zhang, G. Enhanced Stability and Activity of Nitrogen-Doped Carbon Nanotube-Supported Ni Catalysts for Methane Dry Reforming. *Catalysts* **2025**, *15*, 559. https://doi.org/10.3390/catal15060559.
2. Han, Y.; Wang, Z.; Yang, X.; Li, Z.; Li, Y. In Situ Reinforced g-C_3N_4/CoO/CoP Ternary Composite for Enhanced Photocatalytic H_2 Production. *Catalysts* **2025**, *15*, 315. https://doi.org/10.3390/catal15040315.
3. Yan, L.; Jia, Z.; Liu, Y.; Wang, L.; Shi, J.; Qian, M.; He, B. On the Modeling of Continuous H_2 Production by Sorption-Enhanced Steam Methane Reforming. *Catalysts* **2025**, *15*, 246. https://doi.org/10.3390/catal15030246.
4. Khan, W.U.; Putra, A.F.P.; AlMohamadi, H.; Hossain, M.M. Iron-Based Alumina-Supported Catalysts for Clean Hydrogen Production from Ammonia. *Catalysts* **2025**, *15*, 242. https://doi.org/10.3390/catal15030242.
5. Chirinos, C.A.; Liu, S.; Cortés Corberán, V.; Gómez-Sainero, L.M. Effect of Sm_2O_3 Doping of CeO_2-Supported Ni Catalysts for H_2 Production by Steam Reforming of Ethanol. *Catalysts* **2025**, *15*, 131. https://doi.org/10.3390/catal15020131.
6. Ko, Y.; Kim, H.; Kim, S.; Lee, C.; Lee, S.S.; Roh, H.-S.; Shin, J.; Jeon, Y. CO Management for Hydrogen Processes Through a Catalytic Oxidation Mechanism on Dual-Doped Perovskites with Tuned Co and Ni Ratios. *Catalysts* **2025**, *15*, 45. https://doi.org/10.3390/catal15010045.

References

1. Soeder, D.J. Greenhouse Gas and Climate Change. In *Energy Futures. The Story of Fossil Fuel, Greenhouse Gas, and Climate Change*, 2nd ed.; Soeder, D.J., Ed.; Springer: Cham, Switzerland, 2025; Volume 5, pp. 97–141. [CrossRef]
2. Tamor, M.A.; Stechel, E.B. Electrification of transportation means a lot more than a lot more electric vehicles. *iScience* **2026**, *25*, 104376. [CrossRef] [PubMed]
3. Oliveira, D.Q.; Saavedra, O.R.; Santos-Pereira, K.; Pereira, J.D.F.; Cosme, D.S.; Veras, L.S.; Bento, R.G.; Riboldi, V.B. A critical review of energy storage technologies for microgrids. *Energy Syst.* **2025**, *16*, 1063–1092. [CrossRef]

4. Feng, S.; Lazkano, I. Energy storage and clean energy transitions. *Energy Policy* **2025**, *198*, 114447. [CrossRef]
5. Wallington, T.J.; Woody, M.; Lewis, G.M.; Keoleian, G.A.; Adler, E.J.; Martins, J.R.R.A.; Collette, M.D. Hydrogen as a sustainable transportation fuel. *Renew. Sustain. Energy Rev.* **2025**, *217*, 115725. [CrossRef]
6. European Commission. Hydrogen. Available online: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en (accessed on 24 July 2026).
7. European Commission. Renewable Hydrogen. Available online: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/renewable-hydrogen_en (accessed on 24 July 2026).
8. Abed Al Kareem, S.S.; Hassan, Q.; Fakhruldee, H.F.; Hanoon, T.M.; Jabbar, F.I.; Algburi, S.; Khalaf, D.H. A review on physical and chemical hydrogen storage methods for sustainable energy applications. *Unconv. Resour.* **2025**, *8*, 100235. [CrossRef]
9. Dhar, R.P.; Mukherjee, S. Ammonia as a transition fuel for hydrogen economy: A review of ammonia production pathways and combustion characteristics. *Glob. Energy Interconnect.* 2026, *in press*. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.