

Advanced Methods for Hydrogen Production, Storage and Utilization

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Renewable hydrogen plays a critical role in the current energy transition and can facilitate the decarbonization and defossilization of hard-to-abate sectors, such as the industrial, power and mobility sectors [1,2]. Hydrogen holds immense promise as a versatile and sustainable energy carrier capable of addressing various challenges associated with conventional energy sources. Its significance lies in the potential to serve as a clean and efficient alternative across multiple sectors and foster cross-sectorial synergies [3]. Unlike fossil fuels, hydrogen combustion does not produce harmful emissions, making it a crucial element in efforts to mitigate climate change and reduce air pollution. Furthermore, hydrogen's versatility extends beyond energy production, as it can also be utilized as a feedstock in industrial processes, facilitating the transition towards greener and more sustainable manufacturing practices [4,5]. Despite the adoption of policies and implementation of ambitious projects, the widespread adoption of hydrogen must overcome challenges throughout its complete value chain in order to realize its full potential [6,7]. Recent advancements in hydrogen production, storage and utilization methods have garnered significant attention, aiming to address the challenges posed by conventional fossil fuels and pave the way for a greener energy landscape. This Special Issue, "Advanced Technologies for Hydrogen Production, Storage and Utilization", focuses on critical research contributions aimed at advancing the state-of-the-art in green hydrogen technologies, contributing to key issues throughout the hydrogen value chain.

One of the primary hurdles is the high production cost, particularly when using renewable energy sources through processes such as electrolysis. On the other hand, hydrogen production methods, such as steam methane reforming (SMR), contribute significantly to carbon emissions, undermining the environmental benefits associated with the subsequent hydrogen use. The versatility of hydrogen underlines that it can be produced from a variety of feedstocks, diversifying the production portfolio and harnessing feedstocks prevalent in particular locations and conditions. Apart from water electrolysis, addressing the need for cleaner hydrogen production methods, as well as utilizing feedstocks that are widely and locally accessible, is imperative. To this end, methane pyrolysis offers a route for producing clean hydrogen with reduced CO₂ emissions. Neuschitzer et al. (Contribution 1) investigated the production of hydrogen and solid carbon via methane pyrolysis using a liquid metal bubble column reactor (LMBCR). The authors utilized an improved experimental setup and focused on investigating the effect of the process temperature and methane input on methane conversion. At 1160 °C, the authors achieved 40% methane conversion rates, whereas at 1250 °C, 75% conversion was achieved, highlighting the critical role of temperature in the process. In the investigated flowrates (1500–4000 SLM), the authors noted a small decrease in the pyrolysis yield, attributed to different residence times in the tubular reactor section. The findings highlight the potential of the LMBCR technology for hydrogen production, paving the way for further advancements in reactor design, mechanisms and scale-up strategies.

The production and utilization of hydrogen can provide a viable route to achieve near-zero emissions especially for former lignite regions. Kafetzis et al. (Contribution 2)



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focused on the Western Macedonia region's transition to a decarbonized future through the utilization of green hydrogen. The authors presented a comprehensive roadmap outlining the integration of hydrogen across various sectors, including hydrogen utilization for mobility purposes, as refineries' feedstock, natural gas grid injection, heat/electricity generation and added-value chemical production (methane and methanol). The authors categorized the different technologies based on short-, medium- and long-term deployment solutions depending on the required electrolysis capacities, ranging from MW to GW scales. By analyzing the readiness and scalability of different hydrogen technologies, the authors emphasized the levelized approach required for a successful transition. Short-term solutions such as hydrogen for mobility purposes, as refinery feedstock, for gas grid injection and electricity generation could gradually build the necessary capacities for the medium- and longer-term deployment technologies. The study underscored the importance of allowing enough time for phasing out lignite while allowing for hydrogen technologies to catch up so that CO₂ utilization from industries can be also implemented on a large scale. Additionally, environmental assessments provided insights into the potential socio-environmental benefits of hydrogen integration for the region.

Large-scale and cost-efficient hydrogen storage is important to balance production and end-user demands. A suitable storage system can provide seasonal storage of hydrogen and provide continuous supply to industrial applications. Underground hydrogen storage is widely investigated to store large volumes of hydrogen for long timeframes. Borello et al. (Contribution 3) investigated hydrogen diffusion in real caprock samples from natural gas reservoirs that could also be potentially used for hydrogen storage. By estimating diffusion coefficients under realistic and representative reservoir conditions, the authors contribute valuable insights into the feasibility and safety of large-scale hydrogen storage in underground formations. The authors conducted a number of adsorption/desorption tests to calculate the hydrogen diffusion coefficient at different samples and partial pressures. Overall, they suggested that hydrogen diffusion through caprocks was manageable for the under-investigation reservoir. They also highlighted that challenges, such as incomplete or limited desorption, underscore the need for further research to ensure the safety and efficiency of hydrogen storage in underground geological formations.

Ulasz-Misiak and Misiak (Contribution 4) reviewed the important aspects and geological conditions for underground gas storage, focusing on saline aquifers. The research highlighted the importance of site selection, structural characterization, storage capacity and safety assessments for successful gas storage operations. While drawing parallels with natural gas, the study underscored the unique challenges and potential of hydrogen storage in aquifers. In particular, the authors identified several key barriers for the implementation of underground hydrogen storage in saline aquifers leading future research into that direction. Those topics/challenges include geological complexities, safety concerns, technical constraints, infrastructural needs, legal considerations, social acceptance, and potential conflicts of interest.

Finally, hydrogen deployment is critical in order to achieve zero emissions in the mobility sector. Hydrogen is widely investigated as a fuel for the mobility sector and specifically as a fuel for fuel cell electric vehicles (FCEVs). Bacquart et al. (Contribution 5) investigated the influence of hydrogen fuel quality on FCEV performance and durability. In particular, the study presented a novel methodology for evaluating synthetic hydrogen fuels' impact on FCEV performance. The authors conducted real-life testing of the FCEV with controlled levels of contaminants (N₂, CO and H₂S at different compositions) to assess their impact on performance. The findings underscored the need for strict quality standards since small exceedances above the threshold proposed by ISO14687:2019 [8] showed a significant impact on the performance, even with short exposure times. The methodology developed in this study will enable testing a variety of fuel compositions under real conditions and eventually provide insights to hydrogen standardization bodies regarding safe operating ranges of different hydrogen fuel qualities.

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List of Contributions:

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