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Editorial

Advanced Technologies in Hydrogen Revolution

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Hydrogen has been identified as an ideal sustainable energy carrier to meet the ambitious targets of reducing greenhouse gas emissions and the dependence on fossil fuels. It is earth-abundant and can be produced from water without emissions. In addition to being an important industrial feedstock, mainly in the production of ammonia and methanol, hydrogen is used in fields, such as transportation, power generation, and militarized equipment. Hydrogen gas is energy-dense, and can be used in fuel cells where its electrochemical oxidation occurs with high energy conversion efficiencies and without any carbon emissions.

However, the transition from the current petroleum-based economy to a hydrogen-powered future is hindered by issues, such as production costs, investments in infrastructure, storage, transport and distribution, safety considerations, and uncertainties of balancing supply and demand. In particular, hydrogen production costs are at least five times higher than those for fossil fuels. Owing to its low volumetric energy density, hydrogen is normally compressed at high pressures or liquefied. Cylinders that store compressed hydrogen should be capable of withstanding high pressures, and they require expensive composite materials. Moreover, liquefying hydrogen at −253 °C is an energy-intensive process. Steel alloys, which are common storage materials, are unsuitable for storing liquid hydrogen; thus, systematic research on storage materials suitable for cryogenic hydrogen storage is needed.

Furthermore, the lack of proper logistics and infrastructure is a challenge in hydrogen storage and transport. The infrastructure for hydrogen supply needs to be built, which is an immense task that requires political support. In addition, although the pipeline network for natural gas is well-established, retrofitting it for hydrogen is expensive.

The other major barriers in the transition toward a hydrogen-based economy are safety and environmental concerns. Hydrogen is extremely flammable; thus, a hydrogen leak in the presence of air can lead to an explosion when sparked or ignited. In addition, most of the hydrogen produced today comes from the reformation of fossil fuels (gray hydrogen), which is associated with high carbon dioxide emissions—the main cause of global warming. Thus, the production of gray hydrogen emits more carbon dioxide than burning fossil fuels directly. Moreover, the hydrogen produced via hydrocarbon reformation requires extensive processing and purification for use in fuel cell systems, which drives up costs. The alternative is to use green hydrogen, although the production for which requires vast amounts of renewable power. In addition, ultrapure hydrogen is required in fuel cell applications. The high instability and potential for flashback in hydrogen combustion systems are other barriers in the mainstream use of hydrogen as a fuel.

Innovative solutions to these issues using advanced technologies, substantial research, and efforts for development are required to create a viable hydrogen economy. This Special

Issue entitled "Advanced Technologies in Hydrogen Revolution" provides a comprehensive view of the advanced technological aspects of achieving a hydrogen-based economy, including the production [1,2], storage [3–5], infrastructure [6], use of fuel cell technology [7], and influence of fuel used on the power conversion efficiencies and emissions [8,9]. The content of each paper selected for this Special Issue is briefly summarized below.

Khoja et al. conducted experiments to produce hydrogen via methane cracking in a catalytic dielectric barrier-discharge plasma reactor using Ni/$MgAl_2O_4$ [1]. The Ni/$MgAl_2O_4$ nanocatalysts were synthesized using a co-precipitation method followed by a hydrothermal process. The catalyst exhibited a porous spinel structure and was thermally stable. The prepared Ni/$MgAl_2O_4$ catalyst could achieve a methane conversion of up to 80% with >75% hydrogen selectivity, which is better than that observed in the plasma only methane cracking method (hydrogen selectivity of 62%). The tested catalyst was stable for 16-h reaction times, demonstrating that plasma-catalytic methane cracking is a potential technology for green hydrogen production.

It is crucial that green hydrogen production, which involves electrolyzing water using electricity from renewable energy sources (called power-to-gas systems), surpasses conventional hydrogen production. Jovan and Dolanc evaluated the economic viability of green hydrogen production in a typical Slovenian hydropower plant [2]. They reviewed the current hydrogen prices and the cost of the power-to-gas system for green hydrogen production. Hydrogen production can be more profitable than electricity production if sold at rates exceeding 3.86 EUR/kg. Furthermore, profits can increase considerably if hydrogen is produced from the available surplus of electricity. In addition, they found that green hydrogen is already competitive with fossil fuels in the transportation sector, with the assumption that there is no environmental tax for green hydrogen. Furthermore, the combination of hydrogen production and secondary control can result in increased profits when hydrogen is produced dominantly. Accordingly, green hydrogen production from excess available electric energy in a hydropower plant is a promising investment.

Aziz et al. reviewed ammonia as an effective hydrogen storage material that has many advantages over other materials. Ammonia can be stored in the liquid phase under mild conditions, and its distribution network is well-established worldwide with detailed regulations on storage and transportation [3]. After discussing the characteristics of ammonia and comparing hydrogen storage methods, they investigated ammonia production technologies, including the Haber–Bosch process, electrochemical processing, and thermochemical cycle. The storage, transportation, and unitization of ammonia are discussed. Subsequently, the challenges associated with using ammonia for hydrogen storage, such as equilibrium conversion during ammonia decomposition, are addressed, and their possible solutions are deliberated upon.

Aziz et al. focused on liquid hydrogen storage, which has several advantages, such as high purity and density (gravimetric and volumetric), and the opportunity for storage at low pressures [4]. After reviewing the characteristics of hydrogen, representative hydrogen storage technologies were briefly compared. Liquefaction technologies, typical methods to store and transport liquid hydrogen, and global standards and regulations for safely handling liquid hydrogen are discussed. The two main difficulties in liquid hydrogen storage are maintaining a cryogenic temperature of −253 °C and a low ortho–para conversion, needing immediate attention. In addition, the authors emphasized that the regulations and standards for safety in handling liquid hydrogen must be updated regularly, corresponding to the rapid development of industrial-scale transportation and storage, and hydrogen liquefaction technologies. They discussed developments in materials that can endure extremely low temperatures and high-pressure protection instruments, as well as the issues of air condensation and explosion hazard.

Rao and Yoon reviewed various essential aspects in the development of high-performance liquid-organic hydrogen carriers (LOHCs), which are liquid/semi-solid organic compounds that can store hydrogen through hydrogenation and dehydrogenation reactions over numerous cycles [5]. They concluded that LOHC systems with dibenzyl toluene and toluene are the most favorable candidates for industrial production. Nonetheless, additional improvements in LOHC technology are necessary, particularly in terms of thermodynamics. Materials having a lower dehydrogenation enthalpy are preferable owing to the improved substrate recyclability and stability over numerous cycles because hydrogen can be extracted from these materials by supplying a smaller amount of heat.

Vasbiner et al. evaluated the possible risks of building a hydrogen infrastructure project in The Netherlands [6]. An integrated risk assessment scheme was employed to determine the primary risks in the project. Additionally, a time multiplier was added to the framework to develop parameters. The discounted cash-flow model was used to calculate the effects of the various risk classifications given by the framework. Scope is considered the most prominent risk, although resource risks have the most prominent effect on the infrastructure plan. Furthermore, a risk assessment matrix (RAM) was designed to demonstrate the cash-flow model results; it can provide additional data concerning risk details and project profitability.

Ahmed et al. analyzed the behavior of a proton-exchange membrane hydrogen fuel cell (PEMFC) as a grid-connected power generator under different operating conditions, including critical pressures [7]. Using simulations to monitor the efficiency, the optimal operating conditions and air and fuel requirements of the process were determined. The results reveal that PEMFCs operate well under specific fuel and air pressures and can be integrated with electrical grids.

Shadidi et al. examined the effects of hydrogen fuels on the performance and exhaust emissions of spark ignition and compression ignition engines [8]. The production methods and use of hydrogen in engines, either as a direct fuel or secondary fuel, are discussed. Further, the methods to supply hydrogen to internal combustion engines and the corresponding effect on engine efficiency and emissions are explored. The use of hydrogen as a fuel can reduce emissions of carbon monoxide, carbon dioxide, unburned hydrocarbons, and soot; however, it increases the emission of nitrogen oxides. Overall, hydrogen fuel can considerably reduce the release of environmental pollutants in most engines; thus, it is considered a green and sustainable energy source, and its utilization should be expanded in the near future.

Finally, Vigueras–Zuniga et al. conducted a numerical study using innovative reaction models to characterize ammonia combustion systems [9]. The models were designed to apply the Reynolds Averaged Navier–Stokes equations via the Star-CCM+ software (version 19.3) for a 30–70% (mol) hydrogen–ammonia blend. A fixed equivalence ratio of 1.2, medium swirl of 0.8, and confined conditions were applied to determine the flame and species propagation under different atmospheres and inlet temperatures. Subsequently, the study parameters were broadened to include high flow rates, inlet temperatures, and pressures at various confinement boundary conditions.

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References

1. Khoja, A.H.; Azad, A.K.; Saleem, F.; Khan, B.A.; Naqvi, S.R.; Mehran, M.T.; Amin, N.A.S. Hydrogen Production from Methane Cracking in Dielectric Barrier Discharge Catalytic Plasma Reactor Using a Nanocatalyst. *Energies* **2020**, *13*, 5921. [CrossRef]
2. Jovan, D.J.; Dolanc, G. Can Green Hydrogen Production Be Economically Viable under Current Market Conditions. *Energies* **2020**, *13*, 6599. [CrossRef]
3. Aziz, M.; TriWijayanta, A.; Nandiyanto, A.B.D. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. *Energies* **2020**, *13*, 3062. [CrossRef]
4. Aziz, M. Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety. *Energies* **2021**, *14*, 5917. [CrossRef]
5. Rao, P.C.; Yoon, M. Potential Liquid-Organic Hydrogen Carrier (Lohc) Systems: A Review on Recent Progress. *Energies* **2020**, *13*, 6040. [CrossRef]
6. Vasbinder, P.W.M.; de Vries, A.W.G.; Westerman, W. Hydrogen Infrastructure Project Risks in The Netherlands. *Energies* **2021**, *14*, 6009. [CrossRef]
7. Ahmed, K.; Farrok, O.; Rahman, M.M.; Ali, M.S.; Haque, M.M.; Azad, A.K. Proton Exchange Membrane Hydrogen Fuel Cell as the Grid Connected Power Generator. *Energies* **2020**, *13*, 6679. [CrossRef]
8. Shadidi, B.; Najafi, G.; Yusaf, T. A Review of Hydrogen as a Fuel in Internal Combustion Engines. *Energies* **2021**, *14*, 6209. [CrossRef]
9. Vigueras-Zuniga, M.O.; Tejeda-Del-Cueto, M.E.; Vasquez-Santacruz, J.A.; Herrera-May, A.L.; Valera-Medina, A. Numerical Predictions of a Swirl Combustor Using Complex Chemistry Fueled with Ammonia/Hydrogen Blends. *Energies* **2020**, *13*, 288. [CrossRef]