Hydrogen as a Catalyst for Sustainability: Decoding the Value Chain

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The escalating global demand for energy, propelled by rapid economic expansion and population growth, has intensified dependence on fossil fuels, resulting in heightened greenhouse gas emissions and accelerated resource depletion. This pressing scenario underscores the urgent need to transition from conventional energy systems to renewable energy alternatives. Hydrogen has emerged as a compelling energy carrier, poised to facilitate a shift toward a sustainable, low-carbon future. Unlike carbon-based synthetic fuels, hydrogen offers the potential for a carbon-neutral or even carbon-negative lifecycle when produced from renewable energy sources. This review provides a comprehensive and systematic analysis of the hydrogen economy, detailing its value chain from production to practical application and elucidating its potential to support sustainable development.

The analysis encompasses a variety of hydrogen production methodologies, including established techniques such as steam methane reforming and innovative approaches such as electrocatalysis, photocatalysis, biomass conversion, and non-thermal plasma-enhanced dry reforming of methane. This review critically evaluates the processes of hydrogen production, storage, transportation, and utilisation, emphasising its vital role in decarbonising key sectors. Various production methods are assessed based on their efficiency, economic feasibility, and environmental impact, with renewable-driven electrolysis identified as a particularly promising pathway.

In addition, the review examines hydrogen storage and transport technologies, including high-pressure compression, cryogenic liquefaction, and chemical carriers such as liquid organic hydrogen carriers (LOHCs) and metal hydrides, evaluating their technical feasibility and scalability. Furthermore, the study explores the applications of hydrogen in industrial processes, transportation, and power generation, highlighting its potential to substitute carbon-intensive energy sources. Insights from initiatives such as India's National Green Hydrogen Mission are incorporated, addressing critical challenges, including high production costs, infrastructural constraints, and technological limitations.

Progress in material science, process optimisation, and collaboration among academia, industry, and policymakers is essential for surmounting these challenges. Finally, this review delineates key research and development priorities, underscoring the necessity for coordinated efforts to establish hydrogen as a foundational element of a sustainable, low-carbon energy system.