

Green Hydrogen: Promise, Challenges, Future

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Abstract

Green hydrogen is critical for sustainable energy systems and industrial decarbonization. Research highlights its potential but also significant challenges in production efficiency, material costs, and scalability, particularly for water electrolysis and PEM technologies. Safe and cost-effective storage and distribution infrastructure remain bottlenecks. Economic viability hinges on reducing electricity and electrolyzer capital costs. Policy support and investment are essential for widespread adoption. The environmental footprint depends on renewable sources and Life Cycle Assessment boundaries, necessitating careful evaluation for a truly sustainable future.

Keywords

Green Hydrogen; Water Electrolysis; Energy Storage; Decarbonization; Fuel Cells; Sustainable Energy Systems; Biomass Gasification; PEM Electrolyzers; Life Cycle Assessment; Energy Policy

Introduction

The imperative for sustainable energy solutions has brought green hydrogen to the forefront as a pivotal element in the transition away from fossil fuels. It is recognized for its potential to serve as a versatile energy carrier, capable of supporting various sectors and fostering a cleaner future. Recent research has delved into the multifaceted aspects of green hydrogen, from its fundamental production challenges to its broad societal implications.

One significant area of focus is the production of green hydrogen, particularly through water electrolysis. Green hydrogen production via water electrolysis faces hurdles in efficiency, material

costs, and scalability. While it has great potential, catalyst design and system integration require significant advancements to achieve economic viability and widespread adoption. [1]

Sustainable hydrogen production methods are improving, but developing safe, efficient, and cost-effective storage remains a critical bottleneck for wide-scale adoption. [2]

Green hydrogen acts as a sustainable energy carrier, capable of decarbonizing hard-to-abate industries. However, its widespread integration hinges on scaling up renewable energy sources and enhancing conversion efficiencies for production, storage, and utilization. [3]

Green hydrogen can decarbonize industrial sectors, but its adoption requires strong policy support and substantial investment to overcome technological and economic barriers. [4]

Green hydrogen production via biomass gasification presents a promising pathway for sustainable transportation and use in fuel cell electric vehicles. Achieving real-world impact requires overcoming challenges in gasification efficiency and developing more

durable fuel cells. [5]

Proton Exchange Membrane (PEM) water electrolyzers are a key technology for green hydrogen production, offering high efficiency and purity. Improving durability and reducing the cost of precious metal catalysts are critical for widespread adoption. [6]

Green hydrogen will play a crucial role in future sustainable energy systems, offering potential for energy storage and grid balancing. Integrating it can enhance grid stability and reliability, especially with increasing intermittent renewable energy sources. [7]

Generating green hydrogen from renewable energy sources involves a cost highly dependent on electricity prices and electrolyzer capital costs. Significant breakthroughs in these areas are necessary for economic competitiveness. [8]

Green hydrogen holds promise for a sustainable energy future, but building the necessary infrastructure for its efficient and safe production, storage, and distribution remains a significant hurdle. [9]

The environmental performance of green hydrogen production methods varies; its true environmental footprint depends heavily on the specific renewable energy source and the Life Cycle Assessment (LCA) system boundaries. [10]

Collectively, these studies emphasize that while green hydrogen offers immense potential for a sustainable energy future, addressing the technical, economic, infrastructural, and environmental challenges is paramount. The pathway to widespread adoption demands concerted efforts in research and development, policy formulation, and strategic investments. Understanding the intricacies of production efficiency, storage solutions, distribution networks, and the true environmental impact is crucial for realizing the full benefits of this clean energy vector. The journey involves optimizing existing technologies like water electrolysis, exploring new avenues like biomass gasification, and critically evaluating the entire lifecycle to ensure genuinely sustainable outcomes. Here's the thing, achieving a green hydrogen economy is not just about producing the gas; it's about creating an integrated ecosystem that supports its sustainable generation, efficient delivery, and diverse utilization across global industries and energy systems. What this really means is a comprehensive, collaborative approach is essential to navigate the complexities and unlock the transformative power of green hydrogen for a truly sustainable world.

Description

The burgeoning field of green hydrogen research highlights its critical role as a sustainable energy carrier, pivotal for achieving global decarbonization goals. Studies consistently underscore green hydrogen's potential across diverse applications, ranging from industrial decarbonization to enhancing grid stability and fueling sustainable transportation. However, realizing this potential necessitates overcoming a complex array of challenges spanning technological, economic, infrastructural, and environmental dimensions [3, 4, 7]. Here's the thing: understanding these barriers is paramount for guiding future development.

A primary area of investigation centers on the production of green hydrogen, with a significant emphasis on water electrolysis. This method faces substantial hurdles concerning efficiency, material costs, and scalability. Researchers point out that while the technology itself shows great promise, the development of more effective catalyst designs and refined system integration are critical for economic viability and broader adoption [1]. Specifically, Proton Exchange Membrane (PEM) water electrolyzers, recognized for their high efficiency and purity, also require advancements to improve durability and reduce the prohibitive costs associated with precious metal catalysts [6]. Beyond electrolysis, alternative production pathways, like biomass gasification, are being explored for their potential in sustainable transportation applications, particularly for fuel cell electric vehicles. This approach, though promising, demands improvements in gasification efficiency and the development of more durable fuel cells for tangible real-world impact [5]. What this really means is that a diverse portfolio of production technologies is being considered, each with its own set of developmental needs.

Beyond production, the challenges associated with storage and distribution are equally significant and form a critical bottleneck for wide-scale integration. The advancement of sustainable hydrogen production methods is evident, but the development of safe, efficient, and cost-effective storage solutions remains a critical impediment to widespread adoption [2]. Moreover, establishing the necessary infrastructure for the efficient and safe distribution of green hydrogen is a substantial hurdle that requires strategic planning and considerable investment [9]. These infrastructural demands are further complicated by the need for robust policy support and substantial financial commitment to overcome existing technological and economic barriers, especially when considering green hydrogen's role in decarbonizing heavy industrial sectors [4].

The economic viability of green hydrogen is another central

theme in current research, directly influencing its competitive standing against established energy sources. A detailed techno-economic analysis reveals that the cost of generating green hydrogen from renewable energy sources is highly sensitive to fluctuating electricity prices and the upfront capital costs of electrolyzers. This means that significant breakthroughs in reducing these operational and capital expenses are essential for green hydrogen to become economically competitive [8]. Furthermore, the environmental performance of various green hydrogen production methods has been rigorously evaluated using Life Cycle Assessment (LCA). This analysis highlights that despite its "green" designation, the actual environmental footprint of hydrogen is heavily influenced by the specific renewable energy source utilized and the defined system boundaries of the LCA. This critical perspective ensures a holistic and transparent understanding of its true sustainability impact [10].

In conclusion, the collective body of research paints a comprehensive picture of green hydrogen's journey from a promising concept to a tangible component of future energy systems. It stresses the urgent need for continuous innovation in catalyst design and material science, advancements in electrolyzer technology, and the strategic development of robust storage and distribution infrastructures. Policy frameworks and substantial investments are indispensable to catalyze its widespread adoption across industries and energy grids. Ultimately, integrating green hydrogen into the global energy landscape requires a coordinated, multi-faceted approach to address the interwoven technical, economic, and environmental complexities, ensuring it truly delivers on its promise of a sustainable and decarbonized future, capable of enhancing grid stability with increasing intermittent renewable energy sources [7].

Conclusion

Green hydrogen is emerging as a critical component of future sustainable energy systems, offering a path to decarbonize hard-to-abate industries and enhance grid stability. Current research highlights its potential across various applications, from industrial use to sustainable transportation through fuel cell electric vehicles. However, widespread adoption faces considerable challenges. Producing green hydrogen, particularly via water electrolysis, is hampered by issues in efficiency, material costs, and scalability. Significant advancements are needed in catalyst design, system integration, and the overall cost reduction of electrolyzers.

Storage and distribution also represent major bottlenecks. While production methods are improving, developing safe, efficient, and cost-effective storage solutions is crucial. Building the

necessary infrastructure for efficient and safe distribution remains a significant hurdle. Furthermore, policy support and substantial investment are essential to overcome existing technological and economic barriers for its integration into industrial sectors. The economic viability of green hydrogen generation from renewable sources depends heavily on electricity prices and electrolyzer capital costs, underscoring the need for breakthroughs in these areas.

Moreover, the environmental footprint of green hydrogen, though generally considered clean, is highly sensitive to the specific renewable energy source and the boundaries defined in its Life Cycle Assessment. Proton Exchange Membrane (PEM) water electrolyzers, a key technology, require improvements in durability and reduced precious metal catalyst costs. Exploring alternative production methods, such as biomass gasification, also shows promise but demands better efficiency. Ultimately, integrating green hydrogen into the energy landscape requires a holistic approach addressing technological, economic, infrastructural, and policy aspects.

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