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Review paper

Hydrogen as a decarbonization vector: a systematic review of its potential for mitigating environmental pollution in industrial and transportation sectors

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Abstract

The escalating global environmental crisis, predominantly driven by anthropogenic activities, necessitates an urgent and comprehensive paradigm shift away from conventional energy sources. Fossil fuels, which are implicated in a significant proportion approximately 89% of current global pollution, continue to exacerbate climate change, air quality degradation, and ecological destabilization. This underscores the pressing need for cleaner, more sustainable alternatives. Among these, hydrogen gas has emerged as a pivotal contender in the energy transition landscape. This paper presents a systematic review of hydrogen's multifaceted potential to contribute significantly to the decarbonization of both the industrial and transportation sectors. Emphasis is placed on hydrogen's zero-emission combustion characteristics, alongside its synergistic integration with advanced fuel cell technologies, which enhance efficiency and scalability. In addition, the review critically evaluates the environmental and socio-economic benefits inherent in the development of a robust and inclusive hydrogen economy. The transition to hydrogen as a primary energy vector is posited not only as a technically feasible solution but also as a strategic imperative for redressing ecological imbalances and fostering long-term global sustainability.

Keywords: Hydrogen Economy; Climate Change Mitigation; Air Pollution Reduction; Sustainable Energy Decarbonization.

1. Introduction

Air pollution persists as a formidable global environmental dilemma, inflicting substantial negative repercussions on ecosystems, human health, biological entities, and material infrastructure **[1]**. It represents a widespread public health emergency, especially prevalent in both industrialized and developing nations **[1]**. Emissions arising from industrial activities and transportation systems serve as principal factors in the degradation of urban air quality on a global scale. Notwithstanding the enactment of targeted environmental policies, extensive air quality monitoring programs, and robust evaluative frameworks, international endeavors to mitigate air pollution have exhibited limited efficacy. This deficiency can be predominantly attributed to the erratic enforcement of environmental regulations, compounded by the escalating influences of climate change, irregular meteorological conditions, ongoing environmental deterioration, and disturbances to ecological equilibrium. The heterogeneous character of pollution sources and their fluctuating spatiotemporal distributions highlight the imperative for practical and effective mitigation approaches **[2]**.

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The World Health Organization (WHO) **[3]** designates air pollution as the preeminent environmental health hazard on a global scale, accounting for an estimated seven million premature fatalities each year, primarily attributable to oncological, cardiopulmonary, and renal disorders **[4]**. In addition to its well-documented linkage with physical morbidity, exposure to air pollution has been associated with neurological detriments, encompassing expedited cognitive decline and a reduction in intellectual faculties **[5]**. Moreover, emerging economic investigations suggest that these health-related challenges correlate with measurable declines in labor productivity **[6, 7]**. The combustion of fossil fuels across industrial sectors, transportation, energy production, and various anthropogenic activities emits a range of harmful pollutants, including noxious gases, volatile organic compounds, and fine particulate matter (PM) **[4]**. This anthropogenically induced pollution has reached a global magnitude, exhibiting characteristics of being profoundly entrenched and enduring. Air pollution typically exhibits seasonal fluctuations and distinct spatial distributions, frequently influenced by local topographical features and prevailing meteorological conditions **[8]**. As a result, it has developed into a particular manifestation of environmental degradation, distinguished by significant modifications to the natural composition of atmospheric elements. Principal pollutants, such as sulfur oxides (SOx), nitrogen oxides (NOx), greenhouse gases (e.g., CO_2, CH_4), particulate matter (PM_{10} and $PM_{2.5}$), and various hydrocarbon compounds, predominantly arise from the combustion of fossil fuels (including coal, petroleum, and natural gas) as well as biomass sources (such as forest fires, wood combustion, and the incineration of agricultural residues) **[9]**. This discourse posits that a transition towards a hydrogen-centric economy presents a substantial avenue for addressing these urgent environmental and public health issues.

2. The inter nexus of climate change, energy alternatives, and regional air pollution

A substantial body of research on industrial and transportation emissions consistently focuses on three interconnected global challenges: air pollution, energy security, and climate change. The transition to cleaner energy sources like hydrogen has the potential to address these challenges synergistically.

2.1 Climate Change Mitigation through Hydrogen Adoption

Since its inaugural assessment in 1989, the Intergovernmental Panel on Climate Change (IPCC) has persistently underscored the significance of anthropogenic greenhouse gases, particularly carbon dioxide (CO_2) and ozone (O_3), as fundamental catalysts of enduring global warming via the mechanism of entrapment of terrestrial thermal radiation and obstructing its release into the extraterrestrial environment **[10]**. The Arctic Climate Impact Assessment **[11]** issued critical alerts regarding potential catastrophic repercussions, forecasting that unmitigated warming could result in the nearly total desolation of the Greenland Ice Sheet, thereby contributing to a global mean sea-level elevation of roughly seven meters. Esteemed climate scientist James Hansen **[8, 9]** further validated these apprehensions, delineating the observed planetary energy imbalance whereby the Earth absorbs a greater amount of thermal energy than it emits as persuasive evidence (smoking gun) of anthropogenic climate change. Oceanic heat content measurements suggest that even in the context of diminished emissions. a facet of latent warming is expected to endure, thereby exacerbating glacial mass reduction and contributing to sustained climatic volatility **[8]**. Human-induced activities have augmented atmospheric CO_2 concentrations to unprecedented levels not observed in the last three million years **[6-9, 11]**. In light of this anticipated trajectory, both the Intergovernmental Panel on Climate Change (IPCC) and the United Nations leadership, including Secretary-General António Guterres, have emphasized the urgent necessity for "strong and sustained" reductions in carbon emissions to prevent irreversible climatic changes **[10]**. A pivotal transition towards a hydrogen-based economy, with an emphasis on hydrogen fuel cell technologies, is proposed as an essential strategy to mitigate reliance on fossil fuels within the transportation, electricity generation, and industrial sectors **[12, 13]**. The implementation of hydrogen technologies is projected to result in substantial decreases in CO_2, nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter, with anticipated NOx reductions potentially surpassing 70% **[3, 12-20]**. Such a transition possesses the capacity to markedly enhance global air quality and bolster ecosystem resilience **[14-16]**.

2.2 Hydrogen as a Promising Alternative Energy Vector

The simultaneous decline in the availability of natural resources and the increasing severity of ecological degradation has exacerbated the global energy crisis **[21]**. The combined implications of limited petroleum reserves and geopolitical turbulence in significant oil-producing regions underscore the imperative for the investigation of alternative energy trajectories **[2, 4, 5, 6, 8]**. Within the range of viable substitutes including biodiesel, ethanol, methanol, natural gas, and Fischer-Tropsch liquids—hydrogen stands out as the most abundant and energy-rich alternative **[22]**. Despite its absence as a naturally occurring free element, hydrogen functions as a versatile energy carrier, akin to electricity **[23, 24]**. It presents substantial environmental advantages, characterized by the absence of carbon emissions during combustion (water vapor), negligible nitrogen oxide generation under optimized combustion conditions, and significant reductions in pollutant emissions in comparison to methane and gasoline. The swift combustion kinetics of hydrogen, its elevated effective octane rating, and its non-toxic characteristics render it exceptionally appealing for utilization within the transportation and industrial realms **[15]**. The large-scale production of hydrogen can be achieved through a variety of methodologies, including the electrolysis of water facilitated by renewable energy sources (such as solar and wind), steam methane reforming (coupled with carbon capture technology), biomass gasification, and nuclear-driven processes **[20, 22]**. Its capacity for renewable generation positions hydrogen as an integral element in the transition towards a sustainable energy paradigm, thereby enhancing energy security, alleviating urban air quality issues, and fostering economic resilience. The petroleum crisis of 1974 served as a significant impetus for heightened interest in hydrogen as a primary energy vector, a function it is increasingly prepared to undertake within the global energy marketplace **[16]**.

2.3 Impact of Hydrogen Technologies on Regional Air Quality

The transition to hydrogen-fueled vehicles presents significant advantages in the reduction of local air pollution, achieving a decrease in emissions of nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter by an estimated 70–80% **[1]**. Such emission reductions are particularly crucial in densely populated metropolitan areas that are experiencing deteriorating air quality attributable to the combustion of fossil fuels **[18]**. Future energy scenarios consistently indicate an enhanced role for hydrogen, especially in the context of rigorous climate policies, rising fossil fuel prices, and advances in fuel cell technology, hydrogen vehicles, and carbon capture methodologies **[10]**. Forecasts imply that by the year 2050, hydrogen vehicles could potentially cater to 70% of the global populace under ideal circumstances, alongside a simultaneous increase in the deployment of solar energy to facilitate hydrogen production **[22]**. The incorporation of hydrogen into the energy framework not only promises significant environmental and public health advantages but also offers strategic diversification of energy resources and enduring sustainability **[25]**.

3. Discussion

The evidence delineated in this review accentuates the considerable promise of hydrogen as a fundamental element of a sustainable energy paradigm. Its ability to alleviate climate change through zero-carbon combustion, alongside its capacity to diminish regional air pollution by removing deleterious emissions from end-use applications, renders it a persuasive alternative to fossil fuels. The multifaceted nature of hydrogen as an energy carrier, in conjunction with advancements in various production methods, further enhances its feasibility across multiple domains, including transportation, industry, and power generation. Nevertheless, it is imperative to recognize the challenges linked to the extensive implementation of a hydrogen-based economy. These challenges encompass the advancement of economically viable and efficient hydrogen production technologies, the creation of resilient hydrogen storage and distribution infrastructure, and the assurance of safety and public acceptance regarding hydrogen technologies. Continued research and development initiatives are essential to surmount these obstacles and fully actualize the potential advantages of hydrogen.

4. Conclusion

The transition towards a hydrogen-centric economy offers a cohesive trajectory to address essential energy policy goals within both the industrial and transportation sectors. By utilizing hydrogen fuel cells for the generation of electricity and adopting hydrogen as a fundamental fuel vector, this model provides significant prospects for the mitigation of climate change and the reduction of urban air contaminants. Furthermore, hydrogen's distinctive ability to incorporate carbon capture and storage technologies during the production phase (particularly for processes such as steam methane reforming) without the direct release of carbon at the point of utilization positions it as an exceptionally effective instrument for the long-term management of greenhouse gases. Ultimately, a fully operational hydrogen economy is poised to function as a pivotal element in the purification of the atmosphere, the restoration of environmental balance, and the realignment of human endeavors with the natural systems of the Earth.

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

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