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HYDROGEN AS A DECARBONIZATION VECTOR: A SYSTEMATIC REVIEW OF ITS POTENTIAL FOR MITIGATING ENVIRONMENTAL POLLUTION IN INDUSTRIAL AND TRANSPORTATION SECTORS**Muhibbu-Din Eniola Ismail¹⁾, Sanni Mubarak²⁾**^{1,2} Clean Energy/Environmental Research Laboratory (CE2RL),

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ABSTRACT

The escalating global environmental crisis, largely driven by fossil fuel dependency, underscores the urgent need for sustainable alternatives. Hydrogen has emerged as a key candidate for achieving deep decarbonization in industrial and transportation sectors. This study systematically reviews 60 peer-reviewed publications from 2010–2024 to assess hydrogen's environmental, technical, and socio-economic implications. The findings indicate that hydrogen, particularly when produced via renewable electrolysis, offers substantial emission reductions and strong synergy with fuel cell technologies, though infrastructure costs and storage challenges remain critical barriers. The paper concludes that a structured hydrogen economy could significantly enhance global sustainability, provided that supportive policies and investment frameworks are established.

Keywords: Hydrogen Economy: Climate Change Mitigation: Air Pollution Reduction: Sustainable Energy Decarbonization**1. INTRODUCTION**

Air pollution remains a critical global environmental challenge, exerting significant adverse effects on ecosystems, human health, biological organisms, and material infrastructure (World Health Organization [WHO], 2020; Silva et al., 2013). It constitutes a pervasive public health crisis, particularly within industrialized and developing nations (WHO, 2020). Emissions originating from industrial operations and transportation networks are primary contributors to the deterioration of urban air quality worldwide. Despite the implementation of strategic environmental policies, comprehensive air quality monitoring initiatives, and robust assessment frameworks, global mitigation efforts against air pollution have demonstrated limited effectiveness. This inadequacy is substantially attributable to inconsistent enforcement of environmental regulations, exacerbated by the increasing impacts of climate change, anomalous meteorological patterns, ongoing environmental degradation, and disruptions to ecological homeostasis (IPCC, 2014; Shaltami et al., 2020).

The diverse nature of pollution sources and their dynamic spatiotemporal distributions underscores the necessity for pragmatic and efficacious mitigation strategies (De Nicola et al., 2016; Shaltami et al., 2020). The WHO (2020) identifies air pollution as the foremost environmental health risk globally, responsible for an estimated seven million premature deaths annually, predominantly resulting from oncological, cardiopulmonary, and renal pathologies (Silva et al., 2013). Beyond its well-established association with physical morbidity, exposure to air pollution has been correlated with neurological impairments, including accelerated cognitive decline and diminished intellectual capacity (Clifford et al., 2016). Furthermore, emerging economic research indicates that these health

burdens correspond with quantifiable reductions in labor productivity (Hanna & Oliva, 2015; He et al., 2019; Zivin & Neidell, 2018).

The combustion of fossil fuels in industrial applications, transportation, energy generation, and other anthropogenic processes releases a spectrum of deleterious pollutants, such as toxic gases, volatile hydrocarbons, and fine particulate matter (PM) (Sharma & Ghoshal, 2015). Such anthropogenically derived pollution has attained a global scale, exhibiting characteristics of being deeply entrenched and persistent. Typically, air pollution manifests with seasonal variations and distinct spatial concentrations, frequently modulated by local topography and prevailing meteorological parameters (Shaltami et al., 2020). Consequently, it has emerged as a specific form of environmental degradation, characterized by substantial alterations to the natural composition of atmospheric constituents. Key pollutants, including sulfur oxides (SO_x), nitrogen oxides (NO_x), greenhouse gases (e.g., CO₂, CH₄), particulate matter (PM₁₀ and PM_{2.5}), and diverse hydrocarbon compounds, primarily originate from the combustion of fossil fuels (namely, coal, petroleum, and natural gas) and biomass sources (such as forest fires, wood combustion, and the burning of agricultural residues) (IPCC, 2014; Sharma & Ghoshal, 2015). This paper argues that a transition towards a hydrogen-based economy offers a significant pathway to address these pressing environmental and health concerns.

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 (Mazloomi & Gomes, 2012; Sharma & Ghoshal, 2015).

2.1 Climate Change Mitigation through Hydrogen Adoption

Since its initial global assessments, the Intergovernmental Panel on Climate Change has consistently emphasized the role of anthropogenic greenhouse gases, notably carbon dioxide (CO₂) and ozone (O₃), as primary drivers of sustained global warming through the mechanism of trapping terrestrial thermal radiation and impeding its emission into space (IPCC, 2014). The Arctic Climate Impact Assessment issued significant warnings regarding potential catastrophic consequences, projecting that unchecked warming could lead to large-scale cryospheric loss with substantial sea-level rise (International Arctic Science Committee [IASC], 2004). Prominent climate scientist James Hansen further underscored these concerns, identifying the observed planetary energy imbalance—whereby Earth absorbs more thermal energy than it radiates—as compelling evidence (“smoking gun”) of anthropogenic climate change (Hansen, 2005a, 2005b). Ocean heat content measurements indicate that even with reduced emissions, a component of latent warming will persist, thereby intensifying glacial mass loss and contributing to prolonged climatic instability (Hansen, 2005a).

Given this trajectory, sustained reductions in carbon emissions are critical to avert irreversible climatic alterations (IPCC, 2014). A decisive shift towards a hydrogen-based economy—especially hydrogen fuel cell technologies—is proposed as a crucial strategy to displace fossil fuel dependence in transportation, electricity generation, and industry (Muradov & Veziroglu, 2008; Sharma & Ghoshal, 2015). The adoption of hydrogen technologies is anticipated to yield substantial reductions in CO₂, NO_x, volatile organic compounds (VOCs), and particulate matter, with NO_x reductions in end-use applications reported as very large under optimized conditions (Balat, 2008; Sharma & Ghoshal, 2015). Such a transition holds the potential to significantly improve air quality and enhance ecosystem resilience (Muradov & Veziroglu, 2008).

2.2 Hydrogen as a Promising Alternative Energy Vector

The convergence of declining natural resource availability and escalating ecological degradation has intensified the global energy challenge (Romm, 2007). The synergistic effects of finite petroleum reserves and geopolitical instability within key oil-producing regions emphasize the necessity for exploring alternative energy pathways. Among a spectrum of potential substitutes—including biodiesel, ethanol, methanol, natural gas, and Fischer–Tropsch liquids—hydrogen emerges as a versatile, high-specific-energy carrier (Barnwal & Sharma, 2005; Mazloomi & Gomes, 2012; Sharma

& Ghoshal, 2015). Notwithstanding its nonexistence as a naturally occurring free element, hydrogen serves as a flexible energy carrier, analogous to electricity (Mazloomi & Gomes, 2012; Sharma & Ghoshal, 2015). It exhibits considerable environmental benefits, characterized by zero-carbon combustion byproducts (water vapor), minimal nitrogen oxide production under optimized combustion conditions, and substantial reductions in pollutant emissions relative to methane and gasoline (Sharma & Ghoshal, 2015). Hydrogen's rapid combustion kinetics, high effective octane rating, and non-toxic nature render it particularly attractive for applications in transportation and industry (Sharma & Ghoshal, 2015).

Large-scale hydrogen production can be realized through diverse methodologies, encompassing water electrolysis powered by renewables, steam methane reforming with carbon capture, biomass gasification, and nuclear-driven processes (Campen et al., 2008; Muradov & Veziroglu, 2008; Sharma & Ghoshal, 2015). Recent studies also explore renewable-integrated and waste-to-hydrogen routes (Muhibbu-Din et al., 2021, 2022). Its potential for renewable generation positions hydrogen as a crucial component in the transition toward a sustainable energy future, offering enhanced energy security, mitigation of urban air pollution, and the promotion of economic stability (Mazloomi & Gomes, 2012; Muradov & Veziroglu, 2008). The 1974 petroleum crisis acted as a catalyst for renewed interest in hydrogen as a primary energy vector, a role it is increasingly poised to fulfill within global energy markets (Romm, 2007).

2.3 Impact of Hydrogen Technologies on Regional Air Quality

Transitioning to hydrogen-powered vehicles offers transformative benefits in mitigating local air pollution—reducing emissions of NO_x, SO₂, and particulate matter substantially under appropriate control strategies (Balat, 2008; Sharma & Ghoshal, 2015). These reductions are particularly vital in densely populated urban centers facing worsening air quality due to fossil fuel combustion. Future energy analyses consistently project an expanded role for hydrogen, particularly under stringent climate policies, elevated fossil fuel costs, and technological breakthroughs in fuel cells, hydrogen vehicles, and carbon capture technologies (Mazloomi & Gomes, 2012; Muradov & Veziroglu, 2008). Hydrogen's integration into the energy system promises not only environmental and health benefits but also strategic diversification of energy supplies and long-term sustainability (Muradov & Veziroglu, 2008).

3. RESULTS AND DISCUSSION

The evidence presented in this review underscores the significant potential of hydrogen as a key component of a sustainable energy future. Its capacity to mitigate both climate change through zero-carbon combustion and regional air pollution through the elimination of harmful emissions from end-use applications positions it as a compelling alternative to fossil fuels. The versatility of hydrogen as an energy carrier, coupled with advancements in diverse production pathways, further strengthens its viability across various sectors, including transportation, industry, and power generation. However, it is important to acknowledge the challenges associated with the widespread adoption of a hydrogen economy. These include the development of cost-effective and efficient hydrogen production technologies, the establishment of robust hydrogen storage and distribution infrastructure, and ensuring the safety and public acceptance of hydrogen technologies. Further research and development efforts are crucial to overcome these barriers and fully realize the potential benefits of hydrogen (Mazloomi & Gomes, 2012; Muradov & Veziroglu, 2008; Sharma & Ghoshal, 2015).

4. CONCLUSIONS

In summary, the transition to a hydrogen-based economy presents a unified pathway to fulfill critical energy policy imperatives within both industrial and transportation domains. By harnessing hydrogen fuel cells for electricity generation and employing hydrogen as a primary fuel vector, this paradigm affords potent opportunities for climate change mitigation and the abatement of urban air pollutants. Moreover, hydrogen's unique capacity to integrate carbon capture and storage processes at the production stage (for certain methods like steam methane reforming) without directly emitting carbon at the point of use renders it an exceptionally viable tool for long-term greenhouse gas management (Muradov & Veziroglu, 2008; Sharma & Ghoshal, 2015). Ultimately, a fully realized

hydrogen economy emerges as a strategic linchpin for purifying the atmosphere, restoring environmental equilibrium, and realigning human activity with Earth's natural systems.

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