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Towards a Sustainable Future: A Socio-Economic and Legal Review of Green Hydrogen's Role in Pakistan's Energy Transition

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Abstract **- The global commitment to providing sustainable and eco-friendly energy by 2030 has resulted in multiple pilot studies for the development of clean technologies. Green hydrogen is a potential option to ensure sustainable global energy needs. To accelerate its climate objectives, Pakistan has embarked on a strategic transition to green hydrogen in order to reduce dependence on fossil fuels and achieve energy security. This research undertakes a comparative examination of green hydrogen policies in advanced jurisdictions and assesses the viability of strategic shifts within Pakistan's socio-economic and demographic environment to attain energy sovereignty. Adopting a semi-structured qualitative methodology, the research investigates sustainable livelihoods, investment prospects, interoperability mechanisms, and local drivers within Pakistan's policy environment. The research provides critical policy recommendations and proposes a practical model for achieving energy sovereignty. The major challenges identified include production scalability, sectoral consumption patterns, and policy and regulatory alignment. The study is constrained by the limited availability of primary data due to data protection laws in Pakistan.**

Keywords: **Green Hydrogen, Renewable Energy, Sustainability, Clean Energy**

I. INTRODUCTION

The breakdown of water molecules through electrolysis, thermochemical, or biochemical pathways from biomass has been one of the most economically viable options in recent times to achieve carbon neutrality [1]. Pakistan, in line with the United Nations Climate Change Conference (Paris Agreement), has pledged to reduce its carbon footprint and achieve decarbonization [2]. In this regard, investment in green hydrogen infrastructure is viewed as a strategic step toward sustainable energy autonomy and reduced dependence on fossil fuels. To achieve global decarbonization ambitions, Pakistan has set ambitious targets to increase the production of green hydrogen, which will redefine the energy sector by facilitating the shift toward clean energy sources in sectors such as transportation, shipping, aviation, and heavy industries [3]. Figure 1 presents a schematic overview of emerging alternative pathways for green hydrogen production using renewable energy Sources.

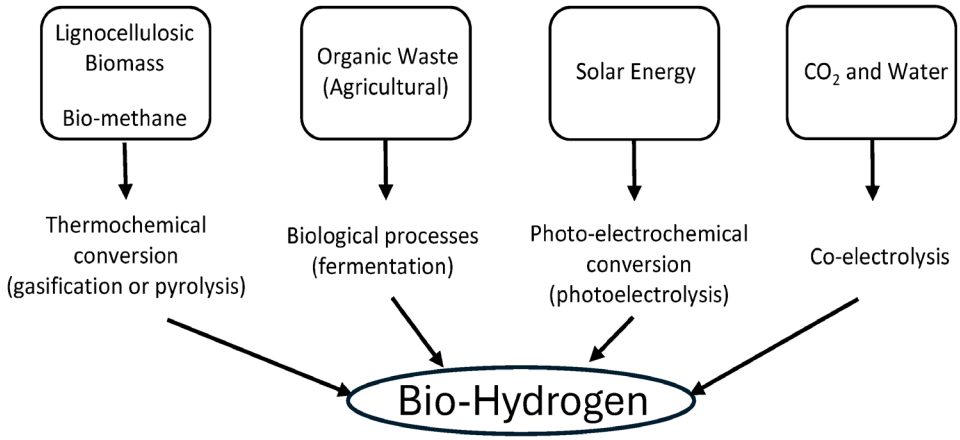

Fig.1 Emerging Alternative Pathways for the Production of Green Hydrogen from Renewable Sources

Recognizing the central role of green hydrogen in the energy transition, the Government of Pakistan has taken proactive steps to build electrolyzer manufacturing capacity and establish pilot projects under a strategic plan for the Green Hydrogen Transition [4]. The aim is to produce at least five million metric tons of green hydrogen per year by 2030 to

address domestic energy needs and establish a sustainable market for hydrogen-based synthetic fuels [5]. This shift will not only substitute fossil fuels but also streamline energy consumption trends in major industrial sectors. To facilitate this transition, global collaboration and cooperation have been prioritized to create infrastructure such as low-carbon emission technologies, manufacturing plants, grid interconnections, and regulatory frameworks [6]. The government has also rolled out financial support, risk protection measures, and foreign direct investment (FDI) avenues to strengthen the green hydrogen value chain and support energy sustainability [7]. For example, investments in green hydrogen production units, the construction of transport and distribution infrastructure, and the establishment of skill development centres are likely to propel the growth of the green hydrogen industry.

As part of its strategic planning, Pakistan's Ministry of Energy has mandated that a considerable portion of the nation's total energy requirements be sourced from renewable energy by 2030 [8]. Various provinces have already initiated regional policies to support the green hydrogen transition. For instance, Punjab has launched a Green Hydrogen and Green Ammonia Policy to establish manufacturing plants and encourage hydrogen production for industrial and transport purposes [9]. Sindh has designated non-usable and arid land for setting up hydrogen production facilities, while Balochistan and Khyber Pakhtunkhwa have outlined renewable energy policies to enable green hydrogen production and meet the increasing energy requirements of heavy industries such as steel, petrochemicals, and fertilizer manufacturing.

Pakistan's green hydrogen development policy includes several key provisions aimed at facilitating the faster uptake of renewable energy. The Energy Conservation Act is used as a basis for simplifying the approval procedures for renewable energy schemes, with an obligation to issue official sanctions for renewable energy supplies within 15 days from the date of application. Financial incentives, such as the exemption of inter-provincial transmission fees for 25 years, provide a significant long-term advantage for green hydrogen projects by lowering overall costs and attracting private investment [10].

In addition, the Green Energy Open Access Rules empower energy distribution companies to provide green energy to a wide spectrum of consumers, including commercial and industrial users [11]. The framework includes a compulsory Renewable Purchase Obligation (RPO), under which energy consumers are required to procure a specified percentage of renewable energy, thereby stimulating demand for green hydrogen [12]. Moreover, the introduction of Green Certificates for consumers of green energy serves as a market-based incentive to encourage renewable energy use and demonstrate corporate social responsibility [13].

These policy initiatives represent a holistic response to the challenges of the energy transition. By targeting both demand and supply, the policy framework seeks to develop a balanced market environment for green hydrogen production. The combined efforts of federal and provincial governments underscore the need for an integrated national approach to accelerating the transition to a low-carbon economy. The success of Pakistan's green hydrogen vision will depend on effective implementation, long-term investment in infrastructure, and the ability to adapt policies in line with technological developments and economic conditions. This transformation not only mitigates environmental challenges but also creates new economic opportunities, strengthens energy security, and positions Pakistan as a leader in sustainable development in South Asia and beyond. Figure 2 presents a forecast of Pakistan's green hydrogen production capacity over the period 2025–2030.

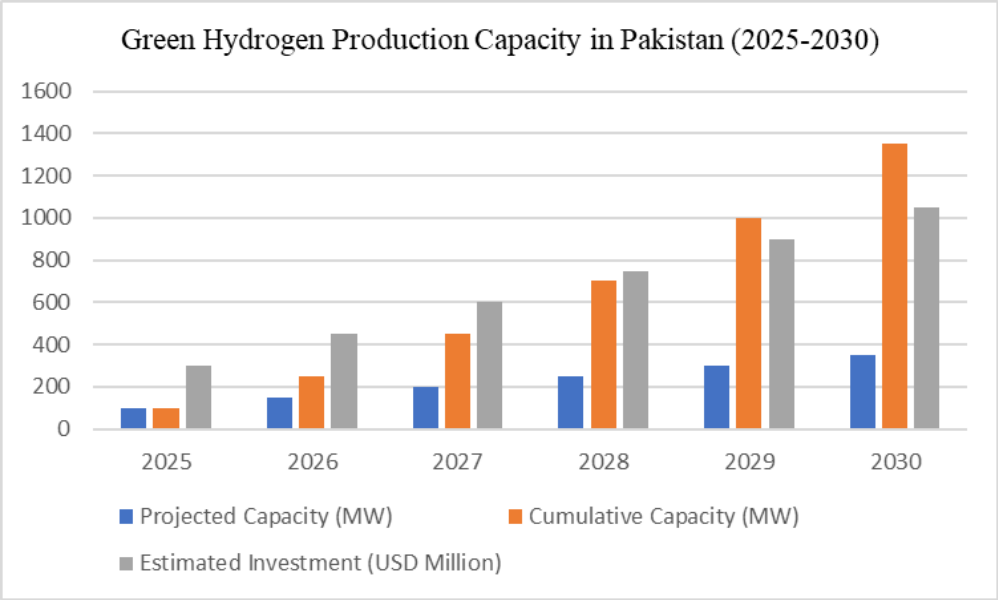

Fig.2 Green Hydrogen Production Capacity in Pakistan (2025-2030)

II. CHALLENGES IN GREEN HYDROGEN ADOPTION AND ENERGY SUSTAINABILITY IN PAKISTAN

The pursuit of carbon emission neutrality in Pakistan poses a multidimensional challenge due to weak financial, infrastructural, and technical capacities. Although the Government of Pakistan has made efforts to collaborate with international bodies and private sector organizations to advance green energy initiatives, a comprehensive and sustainable policy has yet to be instituted [14]. Compared to India's Memorandum of Understanding (MoU) with the European Investment Bank and the India Hydrogen Alliance, Pakistan still needs to establish a focused public–private initiative, such as a Strategic Hydrogen Innovation Partnership (SHIP), to catalyze research and development (R&D) in renewable energy and green hydrogen [15].

A major challenge is the financial insecurity associated with green energy projects. The lack of long-term financial stability restricts the government's ability to offer sustained subsidies and incentives to private enterprises, thereby deterring large-scale participation in renewable energy projects. Financial constraints also limit the scaling up of new green energy solutions, impeding the broader transition toward clean energy [16]. Without adequate financial support, it is difficult to mobilize investments and drive the technological innovations required for green hydrogen production. The regulatory and legal framework for renewable energy and green hydrogen remains fragmented and underdeveloped. Existing policies and operational regulations are largely temporary administrative measures rather than components of a robust legal framework. A fully developed and integrated policy addressing the production, infrastructure, storage, distribution, and consumption of green hydrogen is still absent [17]. In the absence of a codified legal framework, the green hydrogen industry faces uncertainty in regulatory compliance and market stability. This uncertainty leaves investors and industry stakeholders hesitant, thereby constraining the growth potential of green energy. Figure 3 depicts a schematic framework outlining perspectives on green hydrogen production.

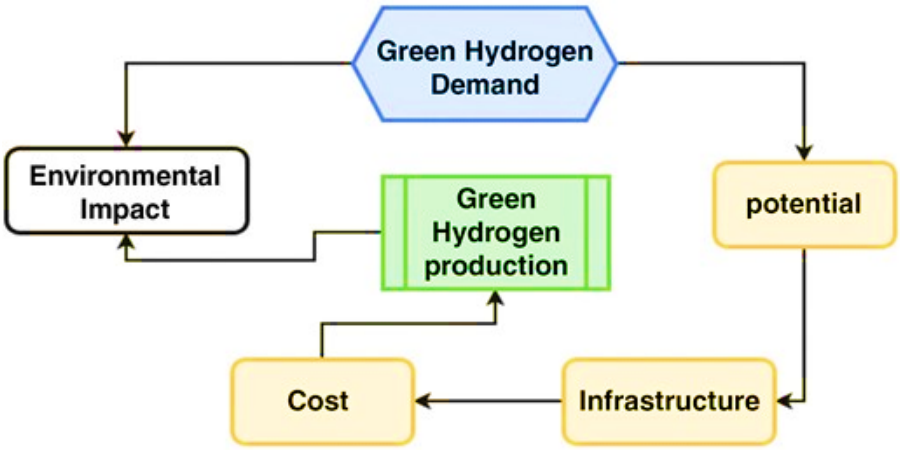

Fig.3 Perspectives in Green Hydrogen Production

Pakistan also experiences considerable resource constraints that make the shift toward green energy challenging.

1. *Water scarcity*: The production of green hydrogen via electrolysis requires large quantities of demineralized water. Pakistan's current water scarcity poses a major obstacle to scaling up hydrogen production.
2. *Land availability*: The availability of land for large-scale renewable energy infrastructure, such as solar and wind farms, is limited by fragmented land ownership and competition with agricultural requirements.
3. *Supply chain issues:* Ensuring a stable supply of raw materials such as copper and rare earth metals, which are critical for renewable energy technologies (e.g., solar panels and wind turbines), is challenging due to fluctuations in global markets and dependence on imports.

Infrastructure costs continue to be a major impediment. Developing a robust supply chain, improving grid-balancing capabilities, and enhancing technological efficiency require substantial capital investment. Pakistan's existing infrastructure capacity is insufficient to support a large-scale green hydrogen transition. The integration of green hydrogen into transmission and distribution networks also necessitates considerable financial and technical resources. Another significant obstacle is the lack of coordination among major sectors. The development of an integrated policy framework requires collaboration across agriculture, waste management, environmental regulation, and technological development. However, Pakistan's energy sector is characterized by isolated efforts and limited inter-agency cooperation, resulting in fragmented progress and missed opportunities for comprehensive advancement [18].

The underutilization of research and development (R&D) in renewable energy is another limiting factor. Despite the growing potential of green hydrogen, research outcomes are not being effectively translated into functional and scalable applications. The gap between academic research and

industrial applicability prevents the sector from fully leveraging advanced technologies for green hydrogen development and storage [19]. Although Pakistan has made notable progress in solar and wind energy, both the production and deployment of green hydrogen remain at an early stage.

Furthermore, end-user demand for clean energy remains sluggish due to limited public awareness and insufficient economic incentives. The Renewable Energy Purchase Obligation (RPO) scheme for distribution companies, although well-intentioned, has not yet generated widespread market demand for green energy. Grassroots adoption of green energy technologies must be encouraged through public awareness campaigns and government-supported incentives. Addressing these challenges requires a paradigm shift in governance and policy. A well-funded, technologically advanced, and coordinated effort involving government agencies, industry stakeholders, and international partners is essential to advance the green hydrogen industry.

Pakistan must establish long-term financial frameworks, strengthen research and development capacities, and design a comprehensive legal framework to support sustainable growth in the renewable energy sector. By overcoming these barriers, Pakistan can position itself as a leader in green hydrogen production and contribute meaningfully to global climate change mitigation efforts [20]. Finally, the lack of coordination across related sectors such as agriculture, waste management, and environmental governance further exacerbates these challenges. A siloed policy environment results in missed opportunities for cross-sectoral collaboration and integrated solutions. Developing a coordinated strategy that aligns green hydrogen initiatives with broader energy, environmental, and economic policies remains a critical requirement.

III. SOLUTIONS

To address these challenges and establish a sustainable green hydrogen industry, Pakistan requires a multi-strategic and multifaceted approach. The following steps are proposed to develop a robust framework for green hydrogen production, transport, and consumption.

1. *Creating an exhaustive legal framework:* A committed legal framework is vital to impart regulatory transparency, investor confidence, and long-term stability. It must address production standards, environmental compliance, and financial incentives to encourage market participation.
2. *Improving resource availability:* Innovative water recycling and desalination technologies can address the shortage of demineralized water. Implementing land consolidation programs and encouraging the use of marginal land for hydrogen production will help resolve land availability challenges.
3. *Building market demand:* Government-initiated programs, such as the mandatory use of green hydrogen in public transport and industrial applications, can drive demand. In addition, encouraging private sector participation through subsidies and tax incentives will help establish a stable market for green hydrogen.
4. *Strengthening financial mechanisms:* The introduction of green financing instruments, such as green bonds and renewable energy funds, can mobilize capital for technological and infrastructure development. Establishing long-term subsidies and incentives for green hydrogen producers and distributors will enhance financial stability and investor confidence.
5. Research and technology innovation investment Enhancing the link between research institutions and industrial players will accelerate the development and deployment of new green hydrogen technologies. Public–private partnerships for R&D will promote technological innovation and market readiness.
6. *Building smart grid and energy storage infrastructure:* Implementing smart grid technologies within the country's energy infrastructure will enhance the efficiency of energy distribution and enable the integration of green hydrogen into the energy mix. Developing advanced energy storage technologies will address the intermittency challenges of renewable energy sources.
7. *Public awareness and stakeholder participation:* Organizing educational campaigns and stakeholder consultations will enhance public awareness and support for green hydrogen projects. Establishing platforms for industry cooperation and knowledge sharing will drive innovation and collective action.
8. *Fostering cross-sectoral coordination:* Creating a central body to coordinate among energy, agriculture, waste management, and environmental agencies will enable a more unified and effective green hydrogen development strategy. It will ensure alignment between national energy and climate policies.
9. *Promoting decentralized energy systems:* Developing local networks for hydrogen production and supply will minimize losses from long-distance transmission and enhance community-level energy security. Decentralized systems will also improve resilience to supply chain disruptions.
10. Finding space for green hydrogen in urban infrastructure Adding green hydrogen infrastructure to smart city planning will make urban areas more energy efficient. Encouraging the use of hydrogen fuel in public transportation, heating, and industrial applications will support long-term market expansion.

Through the adoption of these comprehensive measures, Pakistan can establish a self-sustaining green hydrogen industry aligned with the country's sustainability objectives. This strategic move will position Pakistan as a leader in renewable energy while enhancing energy security, protecting the environment, and driving economic growth.

IV. CONCLUSION

Green hydrogen has game-changing potential for Pakistan's transition toward sustainable energy self-reliance and climate resilience. As this review demonstrates, Pakistan has undertaken decisive policy initiatives, including pilot projects, economic incentives, and regional approaches, to initiate a shift toward green hydrogen. Nevertheless, the country continues to face critical challenges related to financing, regulatory consistency, infrastructure, and sectoral coordination. Addressing these challenges will require a comprehensive legal framework, long-term investment, and participatory governance models that align national development priorities with international climate action. By fostering public–private collaboration, strengthening research and development, and promoting technological innovation, Pakistan can realize the socio-economic and environmental benefits of green hydrogen. This transition not only supports global decarbonization objectives but also presents a significant opportunity for Pakistan to emerge as a regional leader in clean energy innovation.

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