

become imperative for India, not just as a response to environmental concerns but also as a strategy for energy security, economic growth, and social development [2].

Green hydrogen, a form of clean energy derived from water via electrolysis powered by renewable sources like solar and wind, is increasingly recognized as a game-changer in the global energy scene [3]. Capturing the world's attention with its carbon-neutral properties, green hydrogen serves as a viable alternative to fossil fuels [4]. Its role is not limited to just energy; it's versatile, functioning as a fuel, storage medium, and even an industrial feedstock. This flexibility makes it invaluable to nations aiming for diverse and resilient energy portfolios [5]. With abundant renewable resources, especially in solar and wind energy, India isn't just looking at green hydrogen as another energy source. Given the right infrastructure and policies, India could harness its potential to cater to domestic needs and also emerge as a global front-runner in green hydrogen production and export [6].

The benefits of green hydrogen extend beyond its production. It's pivotal in balancing the variable nature of renewables, storing surplus energy, and aiding power generation either directly or through fuel cells. From transforming transportation with hydrogen-fueled vehicles to its application in industrial processes like ammonia synthesis and steelmaking, green hydrogen can dramatically reduce the carbon footprint. Notably, it has an energy density almost triple that of gasoline, making it an efficient storage option that integrates seamlessly with other renewables. This energy source has the potential to decarbonize even hard-to-tackle sectors such as aviation, and its advent could lead to job growth, technological breakthroughs, and the emergence of new markets. Given these multifaceted advantages, green hydrogen is set to be a cornerstone in global decarbonization initiatives [7].

In this research paper, we begin with an introduction, and then shift to discuss the status of green hydrogen. We also explore the broader landscape of India's renewable energy regime, highlighting the many green hydrogen initiatives in place. After laying this foundation, we take a closer look at the National Green Hydrogen Mission. We conclude by summarizing India's progress and potential in the green hydrogen sector.

2. Status of Green Hydrogen

Globally, the significance of green hydrogen has not gone unnoticed. While there isn't a universally binding treaty specifically addressing green hydrogen, various international agreements and protocols focusing on climate change, renewable energy, and sustainability indirectly bolster its relevance. The Paris Agreement, for instance, underscores the importance of transitioning to clean energy sources, [8] with green hydrogen emerging

as a crucial component in many national de-carbonization strategies. Several international forums, such as the Hydrogen Energy Ministerial Meeting and the Clean Energy Ministerial Hydrogen Initiative, have been launched to foster collaboration, share best practices, and accelerate the global hydrogen economy. These initiatives lead to bilateral or multilateral agreements between countries to collaborate on green hydrogen technologies, production, and trade [9]. Recognizing the potential of such collaborations, India has set up bilateral agreements with the United States, Australia, and France to boost research, commerce, and trade prospects. Additionally, India is utilizing multilateral stages like its Group of 20 presidencies to emphasize its green hydrogen endeavors. This effort aligns with the Sustainable Development Goal (SDG) 7, [10] which emphasizes affordable and clean energy, underscoring India's commitment to sustainable energy for all. India's National

Hydrogen Energy Mission (NHEM) harnesses its renewable resources, paralleling global green hydrogen collaborations for a sustainable energy future [11].

Launched in 2020, NHEM exemplifies the nation's drive to pioneer a green hydrogen ecosystem, aiming to establish itself as a global powerhouse in green hydrogen production and export. Central to this Mission is a blend of research, development, and the deployment of green hydrogen, consolidating its role in India's renewable energy vision. Integral to this ambition are states like Gujarat, abundant in solar resources, and Rajasthan, rich in both solar and wind energies. Their geographical advantages, marked by proximity to key industrial zones and ports, magnify their potential contributions [12]. The Mission's broader goals involve fostering green hydrogen technology innovation and translating research into market-ready applications. A distinguishing feature of this initiative is its harmonization with current renewable infrastructures, ensuring that excess energy from solar and wind ventures are effectively channelized into green hydrogen production.

In recognizing green hydrogen's potential for clean energy, India has forged Memorandums of Understanding (MoUs) with countries like Australia [13] and Denmark for technological collaboration and knowledge-sharing. The nation's corporate sector, with giants like Reliance Industries and the Adani Group, is not only responding to the government's push but also visualizing green hydrogen as an emerging market. Reliance Industries, for instance, is on an accelerated path towards green hydrogen dominance by 2025 and

initiating partnerships with original equipment manufacturer (OEMs) [14]. Their plan even extends to distributing hydrogen through their JIO-BP outlets, backed by a \$10 billion investment. Additionally, Gautam Adani has expressed his intentions of setting up a green hydrogen plant in Sri Lanka, an extension of his existing ventures there. Adani has technological agreements for electrolyzers in place, and construction is expected to begin soon [15]. Land for solar and wind projects has been identified. As India moves ahead with its Rs 20,000 Cr Mission by creating green hydrogen hubs, it's clear that both the government and corporates of India see green hydrogen as pivotal. Furthermore, renowned research institutions like Indian Institute of Science (IISc) and the Tata Institute of Fundamental Research (TIFR) are partnering with corporates to innovate in electrolysis and devise economical solutions, signifying a holistic approach to the green hydrogen initiative.

Thus, as the world realizes the potential of green hydrogen in the energy transition, international laws and collaborations are shaping its trajectory. India, aligning its policies with global commitments based on SDG 7 is actively pursuing green hydrogen as a key component of its renewable energy strategy. The corporate sector, sensing the opportunity, is investing and innovating, further bolstering India's position in the global green hydrogen landscape.

3. Indian Renewable Energy Regime

India's journey from a heavy dependence on non-renewable energy sources to a growing emphasis on renewables has evolved significantly over the decades. Until the 1990s, the country's power sector was chiefly overseen by state and central governments, with primary reliance on coal and large hydro projects. This began to shift with the Electricity Regulatory Commissions Act in 1998, which, while focusing on the regulation and reformation of the power sector, also laid the groundwork for promoting renewable energy through the establishment of the Central Electricity Regulatory Commission (CERC) and State Electricity Regulatory Commissions (SERCs).

In the 21st century the Electricity Act of 2003 paved the way for many subsequent reforms in India's energy sector based on Millennium Development Goals (MDGs) [16]. Among its notable introductions was the concept of Renewable Purchase Obligations (RPOs), which mandates certain entities to derive a specific percentage of their power from renewable sources. This was later complemented by the Tariff Policy amendment in 2016, which placed a renewed emphasis on solar energy. The policy set forth an ambitious goal: to achieve 8% of the

electricity mix from solar sources by 2022. While specific policies laid down the framework, the Ministry of New and Renewable Energy (MNRE) emerged as the pivotal governmental agency overseeing new and renewable forms of energy in India. Tasked with the formulation of policies, plans, and programs, the MNRE has been instrumental in driving the nation's green transition.

The later years saw the unveiling of the National Wind-Solar Hybrid Policy in 2018 [17]. Recognizing the complementary nature of wind and solar resources, this policy sought to establish a comprehensive framework for large grid-connected wind-solar photovoltaic hybrid systems. The intent was clear: optimal and efficient utilization of transmission infrastructure. Additionally, in 2015, the Offshore Wind Energy Policy was introduced to harness wind energy beyond India's shores, specifically in the Exclusive Economic Zone. Harnessing offshore wind offers the advantages of consistent and higher wind speeds, reduced land acquisition issues, and the opportunity to generate significant renewable energy, furthering India's commitment to sustainable growth. It's worth noting that the central government's endeavors are complemented by state-specific renewable energy policies. These policies, tailored to the unique resources and needs of individual states, provide added incentives, subsidies, or other advantages to foster renewable projects. For instance, several fiscal incentives, ranging from capital and interest subsidies to customs duty concessions and tax holidays, have been rolled out both by central and state governments to bolster the renewable sector [18].

India has been proactively driving its renewable energy agenda, particularly emphasizing solar and wind energy. One of the foremost initiatives was the National Solar Mission, introduced in 2010 as part of the National Action Plan on Climate Change. The Mission aspired to bolster both grid-connected and off-grid solar applications, with an ambitious goal of reaching 100 GW solar capacities by 2022 [19]. In tandem, the Solar Park Scheme was rolled out, aiming to establish numerous solar parks across the nation. This not only reduces the inherent risks of project development but also furnishes vast stretches of contiguous land with the requisite infrastructure for the seamless establishment of solar projects.

A pivotal initiative targeting the agricultural sector is the KUSUM (Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme. The scheme was authorized by the Cabinet Committee on Economic Affairs in its meeting held in February 2019. It aids farmers in the installation of solar pumps and in the establishment of grid-connected solar power ventures. This progressive scheme is geared towards solarizing India's agriculture, positioning farmers on the path to energy independence. One of the challenges that emerged with the large-scale generation of renewable power was its evacuation to consumption hubs. Addressing this was the Green Energy Corridors project, designed to establish intra-

state and inter-state transmission networks to facilitate the flow of green energy.

In the face of escalating energy demands and the environmental challenges associated with non-renewable sources, India's pre-policy era was characterized by a significant dependence on coal and hydro projects, controlled predominantly by state and central agencies. This reliance not only posed threats to the environment but also restricted the nation's capability to leverage its vast renewable potential, especially in solar and wind energy. However, through the successive rollout of ambitious policies, India has steadily shifted its trajectory towards a more sustainable energy future. These strategic implementations, ranging from the promotion of grid-connected solar and wind projects to innovations like the KUSUM scheme, have fostered energy independence, bolstered economic growth, and considerably reduced environmental footprints. Furthermore, the integration of renewable energy into agriculture and infrastructure underscores India's multi-dimensional approach to progress. The transformation hasn't just been about meeting energy demands; it's been about reshaping India's energy landscape into one that's sustainable, innovative, and economically viable. India's story, thus, stands as a testament to the nation's foresight and adaptability, and the promising results these policies have achieved spotlight the pivotal role of well-defined strategies in steering nations towards a greener tomorrow.

4. Green Hydrogen Initiatives

With the looming threat of climate change, nations across the world are being propelled to reconsider their energy sources and develop a robust strategy to transition away from fossil fuels. As countries grapple with the dual challenges of ensuring energy security and mitigating environmental impacts, green hydrogen has surfaced as a key player in the global energy transition.

The Green Hydrogen Policy introduced in February 2022, advocates for hydrogen production using renewable energy sources, primarily through water electrolysis powered by wind or solar, ensuring carbon-free hydrogen production. Aiming to boost renewable energy capacities and reduce carbon emissions, Maharashtra became a trailblazer on 7th March 2023, introducing its Green Hydrogen Policy. With a generous allocation of Rs 8,562 crore for its implementation, Maharashtra has set a benchmark in India's renewable energy pursuits [20]. Meanwhile, echoing the importance of this transition and addressing the pressing challenges of global warming and climate change, U.P government, initiated the drafting of the UP Green Hydrogen Policy-2023 on 31st August 2023 [21].

Further, in a recent announcement, India's Finance Minister allocated Rs 35,000 crore to prioritize capital investment for the country's transition to cleaner energy,

aiming to achieve carbon neutrality by the year 2070. Additionally, the government has committed Rs 19,700 crore to its Green Hydrogen Mission, setting an ambitious target to produce five million tonnes of green hydrogen by 2030. To further bolster its energy transition initiatives, the government plans to support the establishment of a 4,000 MWh battery energy storage capacity and will introduce a green credit program under the Environment Protection Act [22].

In the lead-up to the G20 Leaders' Summit that happened on 5th September 2023, NTPC organized a conference on "Green Hydrogen Pilots" in New Delhi. As India emerges as the fastest-growing economy with surging power consumption mirroring its growth trajectory, the focus is shifting towards Green Hydrogen and its derivatives to transform the nation from a net energy importer to a net exporter. The Secretary of the Ministry of New & Renewable Energy highlighted a significant budget allocation of Rs 20,000 Cr for the National Green Hydrogen Mission, with an additional provision of Rs 1466 Cr for green hydrogen pilot projects. The event displayed a range of Green Hydrogen initiatives by prominent public and private Indian entities, including NTPC, NHPC, and IOCL, among others. Emphasizing the importance of collaborative endeavors, the seminar underscored the objectives of the National Green Hydrogen Mission [23].

India is making significant strides in the adoption of green hydrogen. By June 2023, the government aims to establish a system for allocating incentives totaling around Rs 1,300 crore, to be dispersed through competitive bidding. This initiative seeks to foster 3.6 million tonnes of GH2 capacity over the forthcoming three years, with a yearly reduction in the incentive amount per kilogram of GH2. In a parallel move, The Solar Energy Corporation of India (SECI) is set to release a substantial tender to consolidate demand for refineries and fertilizer plants. Additionally, Kandla port in the west and Tuticorin port in the east are slated to become India's inaugural refueling stations for green shipping. By 2023's close, eight trains on heritage narrow-gauge tracks are expected to run on hydrogen fuel cell technology [24].

Amid the pressing urgency of climate change, the global shift towards green hydrogen stands as a beacon of sustainable hope. As various nations chart their energy transition, India's proactive measures, epitomized by Maharashtra's trailblazing Green Hydrogen Policy and UP's forthcoming initiatives, signal a transformative era. Events like NTPC's "Green Hydrogen Pilots" conference further emphasize India's commitment, reflecting collaborative efforts to harness hydrogen's potential. Internationally, nations like Japan, South Korea, and members of the European Union are establishing ambitious benchmarks, underlining the collective global intent to pivot towards a cleaner,

hydrogen-powered future. India's infrastructural and policy-driven advancements, including its push for green hydrogen refueling stations and adoption in transport, reaffirm its dedication to spearheading a green energy revolution. The global consensus is clear: green hydrogen is not just an alternative, but a keystone in the arch of a sustainable future.

5. The National Green Hydrogen Mission an Overview

The National Green Hydrogen Mission, approved by the Union Cabinet on 4th January 2022, stands as a testament to this vision. Recognizing the multifaceted potential of green hydrogen, the Mission not only aims to position India at the forefront of green hydrogen production and utilization but also to catalyze a transition away from fossil fuels, foster innovation, and generates significant economic opportunities.

The Mission has been crafted with clear-cut objectives that include positioning India as a global leader in green hydrogen production and supply, creating an export market for green hydrogen and related products, reducing India's dependence on imported fossil fuels, catalyzing indigenous manufacturing capabilities, attracting substantial industry investment, promoting job creation, and fostering research and development initiatives [25].

By 2030, the Mission envisions establishing a production capability for green hydrogen of a minimum of 5 MMT per annum, boosting associated renewable energy capacity to around 125 GW, mobilizing over Rs. Eight lakh crore in total investments, creating over six lakh job opportunities, reducing annual fossil fuel imports significantly, and abating nearly 50 MMT of greenhouse gas emissions annually. To facilitate these goals, a sum of Rs 19,744 crore has been approved for the Mission. This funding is distributed across various initiatives, notably the Strategic Interventions for Green Hydrogen Transition Programme (SIGHT) which aims to fund domestic electrolyser manufacturing and promote green hydrogen production, and the initiative to identify and develop states and regions as Green Hydrogen Hubs, emphasizing areas with the potential for large-scale hydrogen production and utilization. On July 5, 2023, the MNRE unveiled a draft R&D roadmap for India's green hydrogen ecosystem, emphasizing research initiatives for hydrogen production, storage, and transport. The roadmap outlines strategies for mid and long-term projects and proposes public-private collaboration called the Strategic Hydrogen Innovation Partnership (SHIP) to bolster R&D with funding from both industry and government [26].

India's National Green Hydrogen Mission stands as a significant move towards harnessing green hydrogen as an eco-friendly fuel. Firstly, the high production costs of green hydrogen, predominantly from electrolysis,

overshadow those of grey or blue hydrogen, necessitating technological progress and economies of scale for cost reduction. Secondly, the prevalent infrastructure, tailored for fossil fuels, mandates substantial investments for hydrogen integration, spanning production facilities to transport systems. Thirdly, with hydrogen's low energy density, efficient storage and large-scale transportation present considerable challenges. Fourthly, it's imperative to ensure the electricity for electrolysis is derived from renewable sources for genuinely classifying the hydrogen as "green." Lastly, the hurdle of public perception looms large, widespread adoption by industries and the public hinges on effective awareness campaigns. Therefore, a comprehensive approach to these challenges is pivotal for the Mission's triumph.

2022's National Green Hydrogen Mission, initiated in 2022, demonstrates a bold and visionary step towards a sustainable energy future. With ambitious targets set for 2030, the Mission seeks to place India at the helm of global green hydrogen production and reduce its fossil fuel dependence [27]. While challenges persist, ranging from high production costs to infrastructure modifications and public perception, the combination of clear objectives, significant investment, and a focus on R&D offers hope. For the Mission to truly succeed, a holistic approach addressing these challenges is essential. As India propels forward, the nation stands poised to redefine its energy landscape, fostering innovation, boosting the economy, and championing SDG7 (affordable and clean energy) responsibility.

6. Prospective Horizons of the Green Hydrogen Mission

Green hydrogen stands at the crossroads of innovation, economic rejuvenation, and environmental responsibility. As nations pivot to this transformative energy source, its impact promises to ripple across industries, economies, and global collaborations, heralding a future powered by sustainable solutions. Firstly, the effects of a green hydrogen-focused approach could rejuvenate the very fabric of our economies due to the infrastructure required for its production, storage, and distribution which promises a surplus of job opportunities, spanning from groundbreaking research to logistics [28]. Secondly, as a promising sector, green hydrogen beckons nations to invest, innovate, and potentially lead in this transformative industry. Thirdly, on the economic front, it offers nations the chance to diversify their energy matrix, enhancing energy security by reducing fossil fuel dependency. Fourthly, the industrial realm, particularly carbon-laden sectors such as steel and chemicals, is set for a radical metamorphosis by leveraging green hydrogen as an alternative energy source or raw material, marking strides towards greener industrial processes. Fifthly, the transportation sector stands on the precipice of innovation with hydrogen-fueled vehicles, especially for heavy-duty tasks, offering rapid refueling and

extended range, setting them apart from conventional battery-operated counterparts. Sixthly, from a global perspective, nations that pioneer robust green hydrogen systems can turn into exporters, catering to regions with scant renewable resources. This export potential emphasizes technological progress, from improving electrolysis methods to devising cutting-edge storage techniques. Seventhly, the environmental benefits of green hydrogen extend beyond just reducing carbon footprints, promising enhanced air quality and diminishing risks of disasters such as oil spills. Lastly, as the global fervor around green hydrogen grows, it will inevitably spark international collaborations, fostering technological exchanges and integrated supply chains, and solidifying the emergence of a world unified by the Mission of green hydrogen [29].

Conclusion

India's National Green Hydrogen Mission serves as a compelling testament to the nation's unwavering commitment to sustainable energy, outlining a clear vision of India as a global forerunner in green hydrogen. Within the broader canvas of the Renewable Energy Regime, India's dedicated Green Hydrogen Initiatives showcase an integrated approach that melds technology, policy, and public awareness. These initiatives, steeped in ambition, seek to embed green hydrogen into the very fabric of the country's energy landscape, propelling transformative shifts in sectors from transportation to manufacturing. As India charts this course, it refrains from being a mere spectator and instead establishes itself as a forerunner in green hydrogen innovation.

Though green hydrogen shines brightly as a symbol of hope, it has noteworthy challenges. The journey of green hydrogen, especially under the umbrella of India's Mission, faces tangible obstacles. From high production expenses and infrastructural overhaul demands to challenges posed by hydrogen's low energy density and the need for genuine "green" energy sourcing, the path is replete with intricate challenges. Additionally, public perception, guided by effective outreach and communication, can serve as either a propellant or a hindrance in this journey. It's essential to understand that green hydrogen could be a vital tool in addressing climate change and play a significant role in India's renewable energy regime, aiding in the achievement of SDG7. Wherein it is pivotal to recognize that beyond these hurdles is a vast expanse brimming with opportunities. Green hydrogen, from rejuvenating economies to leading the charge in green industrial practices, signals a future filled with innovation, collaboration, and purpose, going beyond just addressing climate change to fostering sustainable growth.

As trailblazers like India navigate this path, the global paradigm is on the threshold of an epoch where challenges are no longer impediments but catalysts,

forging a luminous future anchored in clean energy through global partnership towards sustainable development.

Acknowledgements.

I would like to express my sincere gratitude to Dr. Sandhya Kumari for her invaluable contributions and expertise in the writing of this research paper.

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