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INDIA'S GREEN HYDROGEN: FEASIBILITY AND FUTURE

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INTRODUCTION:

Hydrogen production involves utilizing a variety of feedstocks, both renewable and non- renewable, through diverse processes that yield varying levels of greenhouse gas emissions. [1] The usage of traditional fossil fuels like oil for energy generation leads to a notable increase in greenhouse gas emissions. The combustion of these fuels releases substantial amounts of carbon dioxide and other greenhouse gases into the atmosphere, exacerbating atmospheric warming and impacting global temperatures. The issue of global warming is of paramount importance on the international stage, and India, representing approximately 36% of the global population, is actively engaged in efforts to mitigate its effects. The adverse ramifications of the climate crisis encompass elevated temperatures, ecological degradation, erratic rainfall patterns, and population displacement.[2] The primary challenge in curbing emissions within energy sectors arises from the heavy dependence on fossil fuels, which account for the majority of CO2 emissions across various sectors such as electricity generation, construction, heating, transportation, and industrial processes.[3] The predominant hurdle in mitigating emissions within energy sectors stems from the extensive reliance on fossil fuels, which constitute the main source of CO2 emissions across diverse sectors including electricity generation, construction, heating, transportation, and industrial processes.[4]

The climate crisis, resulting from human intervention in various activities, stands as one of the most pressing challenges facing society. To address this crisis, efforts must prioritize the decarbonization of energy systems across all sectors. At present, the world is facing a pivotal moment in the energy transition, marked by the rise of low-carbon technologies replacing traditional fossil fuel assets and setting new energy benchmarks. By integrating renewable energy sources such as wind, solar, and hydropower, we can address the growing demand for energy, combat the effects of climate change, and reduce air pollution. Nevertheless, certain sectors, such as manufacturing and heavy transportation, present challenges in adopting low- or zero-carbon technologies.[5] Currently, a significant portion of hydrogen production relies on fossil fuels. However, the production of green hydrogen offers a solution by reducing carbon emissions and potentially decreasing production costs.[6] Green hydrogen holds promise in addressing these challenges and facilitating the decarbonization of sectors that are difficult to transition away from fossil fuels.

UNDERSTANDING KEY CONCEPTS:

1. *Grey, Blue and Green Hydrogen:*

Although hydrogen is abundantly available on Earth, it primarily exists in molecular compounds like water or natural gas, requiring sophisticated methods like reforming or electrolysis to extract its pure form. As the fundamental constituent of the chemical elements, hydrogen manifests as an

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achromatic, scentless, insipid, yet highly flammable gas. It has the capability to be stored in large quantities for extended periods of time.[7]

There are various forms in which hydrogen can be utilized by corporations in order to complete their production process. In terms of business and how the hydrogen is being procured various colors are given to hydrogen. Both green hydrogen and grey hydrogen are not the actual colors of hydrogen but basically provide us with the ways in which hydrogen is being procured in order to produce energy for future productions. These kinds are discussed below:

Grey Hydrogen:

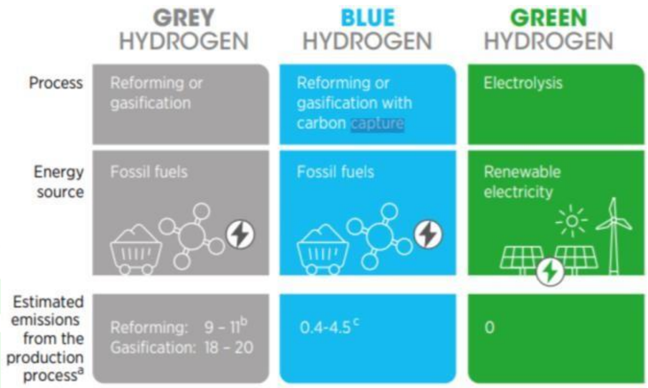
Producing grey hydrogen, accomplished via steam reforming fossil fuels like natural gas or coal, presents notable environmental concerns. This is due to the release of ten tons of CO2 for every ton of hydrogen generated. Additionally, grey hydrogen can also be generated when electricity from non-renewable energy sources is utilized alongside renewable energy for water electrolysis.

Blue Hydrogen:

Blue hydrogen is produced via a technique known as steam reforming, which involves the reduction of natural gas using steam. Through this process, both carbon dioxide and H2 are isolated from the natural gas. Notably, CO2 is not discharged into the air; instead, it is either stored or subjected to industrial treatment. Carbon Capture and Storage (CCS) technology enables the underground storage of CO2, offering a means to minimize its release into the atmosphere.

Green Hydrogen:

Hydrogen can alternatively be generated by electrolyzing water, using electricity sourced from renewable energy. The environmental friendliness of this process depends on the carbon neutrality of the electricity source. Put differently, the higher the proportion of renewable energy in the electricity fuel mix, the more environmentally friendly ("greener") the production of hydrogen becomes.[8]



2. ***How is Green Hydrogen Produced:***

Several methods are available for producing green hydrogen, including alkaline polymer electrolyte membrane electrolysis (PEM), water electrolysis, anion exchange membrane electrolysis, steam reforming, and fermentation. In India, alkaline and PEM electrolyzers are considered the two most commercially viable approaches for green hydrogen production, offering versatility in utilizing both renewable and non-renewable energy sources. However, traditional fossil fuels remain predominant in hydrogen production, with costs ranging from

$1.34 to $2.27 per kilogram (approximately ₹100 to ₹200 per kilogram). Notably, hydrocarbon reforming and pyrolysis emerge as well-established methods in the domain of hydrogen production. Hydrocarbon reforming employs reforming techniques to convert hydrocarbon fuel into hydrogen. Steam reforming involves catalytically converting hydrocarbons, while partial oxidation converts steam and hydrocarbons into hydrogen and CO2. Autothermal reforming combines exothermic partial oxidation, resulting in increased rates of hydrogen production.

On the other hand, pyrolysis entails the thermal breakdown of hydrocarbons. Although both approaches consume hydrocarbons, the pressing concerns of depleting fossil fuel reserves and global warming emphasize the necessity of transitioning towards renewable sources for hydrogen production. From an economic standpoint, grid-based electrolytic hydrogen production offers benefits through the efficient utilization of electrolyzers, particularly when paired with renewable energy sources. This can lead to a notable reduction in the production cost of hydrogen from electrolyzers, potentially reaching around $12.6 per kilogram (approximately ₹900 per kilogram), contingent upon variables such as electricity tariffs, transportation, and storage expenses.[9]

So, to conclude hydrogen production spans various methods, utilizing both renewable and non-renewable sources, each with distinct environmental impacts. While conventional fossil fuels dominate, the emergence of green hydrogen, generated through processes like electrolysis with renewable energy, offers a promising solution. The shift towards renewable sources is crucial amidst concerns over greenhouse gas emissions and fossil fuel depletion. Hydrogen's color-coding - grey, blue, and green - delineates its production methods and environmental implications. The transition to green hydrogen, driven by technologies like electrolysis, signifies a pivotal step towards sustainable energy systems, albeit challenges persist, notably in cost and technological adoption.

CURRENT FRAMEWORK OF GREEN HYDROGEN IN INDIA:

The Hydrogen Policy, unveiled by the Indian government in 2022, highlights the increasingly unanimous global agreement regarding the pressing necessity to address global warming. The focus is on limiting the increase in global temperatures to below 2 degrees Celsius, with an ambitious goal of capping it at only 1.5 degrees Celsius above pre-industrial levels. Numerous countries, India included, have committed to their Nationally Determined Contributions (NDCs) to expedite the transition to sustainable energy and reduce emissions, with a specific focus on attaining net zero objectives. The pivotal shift towards utilizing Green Hydrogen and Green Ammonia in order to combat emissions, particularly in industries that prove difficult to decarbonize, has been recognized. To facilitate the shift from fossil fuels to greener alternatives, the Indian government is considering a variety of policy interventions. These measures aim to promote the widespread adoption of Green Hydrogen and Green Ammonia as energy sources and chemical components in various sectors.

INDIAN GOVERNMENT'S POLICY[10]

The Indian government has introduced a comprehensive policy framework known as the Hydrogen Policy to address the evolving global environmental challenges and maintain sustainable temperatures. To advance the utilization of green hydrogen in India's energy landscape, several strategies must be implemented.

Firstly, policymakers should continually refine policies to explicitly support green hydrogen production and usage, ensuring clear incentives for investment while imposing strict regulations on high-carbon alternatives. Mobilizing investments from both domestic and international sources is crucial, necessitating partnerships between the public and private sectors to accelerate infrastructure development and research initiatives. Priority should be given to expanding infrastructure tailored to green hydrogen, including electrolysis plants, storage facilities, and transportation networks. Moreover, promoting technological innovation through research and development efforts is vital, requiring collaboration with global leaders in hydrogen technology to drive progress in cost reduction and efficiency enhancement. Integrating renewable energy sources, especially solar and wind power, is essential to provide clean electricity for green hydrogen production, necessitating strategies that align renewable energy projects with green hydrogen initiatives.

Moreover, allocating resources to training and educational initiatives is paramount for nurturing a proficient workforce capable of bolstering the expansion of the green hydrogen

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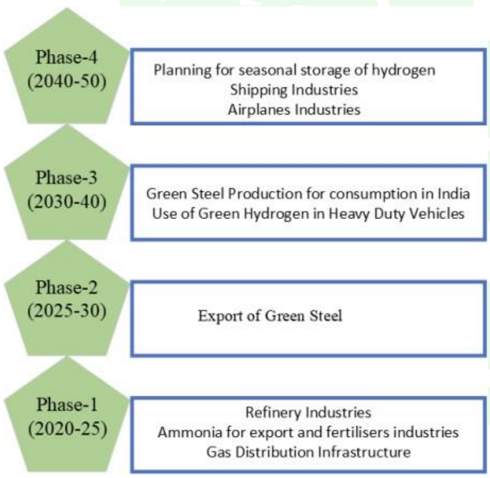
sector. Strengthening partnerships with other countries and international organizations is imperative to exchange knowledge, resources, and best practices, driving collective efforts toward a hydrogen-based economy. Launching targeted public awareness campaigns and initiating pilot projects in key sectors will demonstrate the viability and effectiveness of green hydrogen applications, paving the way for broader implementation.

Finally, aligning incentive mechanisms such as subsidies and tax incentives with the specific requirements of green hydrogen production and usage will stimulate demand while encouraging innovation and market growth. By enacting these measures, India can harness its renewable energy capacity and strategic alliances to expedite the shift towards a green hydrogen economy, positioning itself as a frontrunner in sustainable energy generation and playing a substantial role in global climate change mitigation endeavors.



With the policies being formulated to reduce global warming and moving to more greener ways to generate hydrogen it is important to understand India's roadmap for green hydrogen. There has been a noticeable increase in demand for hydrogen on a global scale, with different types of hydrogen available depending on the production process. One such type is green hydrogen, which incorporates renewable energy sources in its production. Table I provides an overview of the demand for hydrogen in various countries across different sectors, as well as an outline of strategies for the development of hydrogen. India is placing a strong emphasis on Green Hydrogen to achieve its National Hydrogen mission by 2050. Steps are being taken to explore the potential uses and opportunities for integrating Green Hydrogen in India. The Indian government is actively rolling out policies to bolster the NHM, with the aim of positioning India as a prominent Global Green Hydrogen Production and Export Hub. This integration will unfold in four distinct phases. Initially, spanning from 2020 to 2025, the focus will predominantly revolve around the fertilizer and refining sectors. Transitioning to the subsequent phase, spanning from 2025 to 2030, the emphasis will shift towards the exportation of green steel. Subsequently, in the third phase spanning from 2030 to 2040, priority will be given to the domestic steel industry and the uptake of green hydrogen in heavy-duty vehicles. Finally, in the concluding phase from 2040 to 2050, there will be heightened attention towards seasonal storage, maritime industries, and aviation.

FEASIBILITY AND FUTURE PROSPECTS OF GREEN HYDROGEN IN INDIA

FUTURE PROSPECTS

India's interest in hydrogen has been growing because of its potential to solve issues with energy security, lower carbon emissions, and open up new business opportunities. India's strong prospects for green hydrogen can be attributed to several fundamental aspects. Solar and wind power are two of India's many renewable energy resources. India can meet its emission reduction targets and advance energy independence by using these resources for electrolysis to produce green hydrogen.[11]

Through a number of laws and programs, the Indian government has been aggressively advancing clean technologies and renewable energy.[12] The National Hydrogen Mission, for example, seeks to advance the research and use of H2 as a fuel in a variety of industries.[13] A

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number of Indian sectors, such as refineries, steel, and fertilizer, have substantial energy needs and presently rely on fossil fuels. For these sectors, green hydrogen provides a clean substitute that could lessen their carbon footprint. To develop green hydrogen technologies, India is taking part in international partnerships and collaborations. Collaboration with nations that are at the forefront of hydrogen technology, like Germany, Australia, and Japan, can help to advance investment, technology transfer, and information sharing in the field. These collaborations aim to accelerate the advancement and adoption of green H2 by leveraging the expertise, assets, and technological capabilities of both India and its partner countries.

COLLABORATION WITH COUNTRIES:

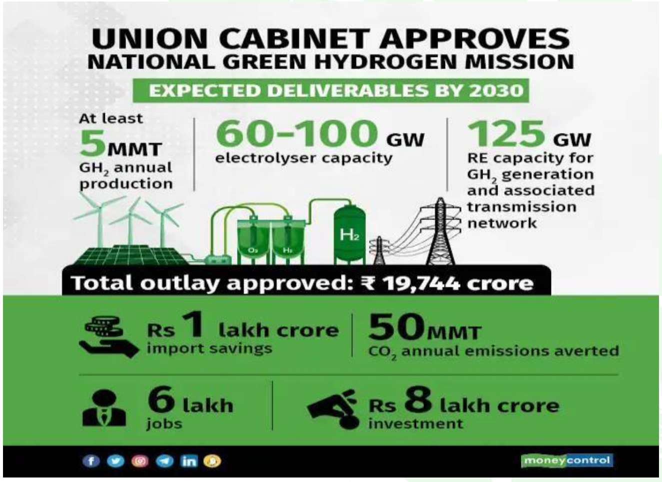
- Australia and India have been exploring avenues for collaboration in the field of green hydrogen and renewable energy.[14] Both nations have an abundance of solar and wind energy, which makes them the perfect collaborators for creating massive green hydrogen projects. India and Australia have established bilateral agreements and partnerships with an emphasis on collaborative research, technology sharing, and investment in green hydrogen infrastructure.[15]
- Germany and India have collaborated to advance research and development in the production, storage, and utilization of green hydrogen. These collaborations include cooperative projects, knowledge sharing, and efforts to increase capacity in order to spur innovation and accelerate the deployment of green hydrogen.[16]
- In order to promote collaboration in the field of green hydrogen, India and Japan have partnered. This cooperation will take the shape of cooperative research, technological transfer, and demonstration projects. These partnerships seek to expedite the shift to a hydrogen-based economy by using India's renewable energy potential and Japan's hydrogen technology know-how.[17]
- In order to advance green hydrogen activities, bilateral talks and partnerships have been taking place between the United States and India. To spur innovation and accelerate the implementation of green hydrogen in both nations, these relationships span a range of domains, including policy discourse, investment in green hydrogen initiatives, and research collaboration.
- India aims to enhance its standing as a worldwide pioneer in renewable energy and progress its endeavours towards attaining carbon neutrality by means of these bilateral agreements. India hopes to speed the shift to a sustainable and hydrogen-based energy future by collaborating with these nations. To increase the effectiveness and affordability of green hydrogen production technologies, Indian organizations and businesses are actively engaged in research and development. Research and innovation expenditures have the potential to quicken India's movement towards green hydrogen.

But there are still a number of obstacles to overcome, such as high production costs, building infrastructure, and increasing output to keep up with demand. It will take coordinated efforts from the public, business, and research organizations to overcome these obstacles. Overall, given India's capacity for renewable energy, government backing, and increased interest from businesses and foreign partners, the country's prospects for green hydrogen are positive. Encouraging investments in infrastructure, governmental assistance, and technology development will be necessary to fully utilize green hydrogen in India's energy transformation.

INDIA'S GREEN HYDROGEN MISSION

The mission's overarching aim is to cultivate a thriving export market for green hydrogen, along with its accompanying by-products, such as the esteemed green ammonia. This endeavour seeks to diminish reliance on imported fossil fuels while simultaneously decarbonizing vital sectors, including power, transportation, and industry.[18] Strategic Interventions for Green Hydrogen Transition (SIGHT) Programme: This initiative provides financial incentives for the generation of green hydrogen domestically, as well as for the manufacturing of electrolysers, which are equipment used in the process. The goal is to provide funding for pilot programs that investigate and illustrate the potential uses of green hydrogen.

By pinpointing and cultivating regions with



substantial potential for producing and utilizing green hydrogen, the initiative aims to create Green Hydrogen Hubs that come equipped with necessary infrastructure. The mission allocates funds to research and development endeavours aimed at improving green hydrogen technologies and reducing production expenses.[19]

The energy sector in India could be greatly impacted by the Green Hydrogen Mission. Around 600,000 jobs are expected to be created along the green hydrogen value chain. By 2030, the mission may draw large investments totalling more than $96 billion. Green hydrogen can help India achieve its clean energy targets and lower greenhouse gas emissions by taking the place of fossil fuels.

The mission to promote hydrogen is still in its early phases. The government is now developing comprehensive policies and procedures for carrying out the several mission components.[20]

CHALLENGES RELATED TO PRODUCTION OF GREEN HYDROGEN

Electrolysis emerges as the principal technique for producing green hydrogen, hinging on electricity sourced from renewables such as solar or wind power. Despite the declining expense of renewable energy, electrolysis persists as relatively costlier compared to alternative methods, especially those leveraging fossil fuels for hydrogen generation.[21]

A challenge in green H2 production stems from the unpredictable nature of renewable energy sources such as solar and wind. Fluctuations in weather patterns can disrupt the consistent supply of electricity required for electrolysis plants. To realize cost efficiencies through economies of scale, the production of green hydrogen needs to be scaled up to industrial levels. But this calls for a large investment in technology and infrastructure, which might be prohibitive for many nations and businesses.[22] Because of its low energy density, hydrogen requires specialized infrastructure for both transportation and storage. Without modifications or enhancements, the existing natural gas infrastructure, often repurposed for hydrogen transport, may not be suitable for the widespread distribution of green H2.[23] At the moment, grey hydrogen which is derived from fossil fuels that emit carbon dioxide is less expensive than green hydrogen. Green hydrogen producers face a hurdle as a result of this pricing differential. They need to figure out how to remain competitive while yet preserving environmental sustainability. Investment in green H2 production and infrastructure may be hampered by unclear or inconsistent government policies and regulations. To provide developers and investors trust, clear and consistent policies are required.[24]

To increase the effectiveness and lower the prices of electrolysis and other environmentally friendly hydrogen generation techniques, further research and development is required. Technological innovations have the potential to greatly increase green hydrogen's competitiveness in the future. Governments, business partners, and academic institutions must work together to address these issues in order to spur innovation, cut costs, and establish an environment that supports the production and use of green H2. Green hydrogen is anticipated to become more competitive with traditional hydrogen generation techniques as technology develops and economies of scale are realized, propelling its adoption as a clean energy source.[25]

INITIATIVES FOR GREEN HYDROGEN ADVANCEMENTS:

India has been involved in a number of agreements and collaborations with other nations about green hydrogen. The principal objective of these agreements is to promote collaboration in the areas of green hydrogen technology research, development, production, and application. India has been actively involved in debates and projects involving green hydrogen, as have its fellow members of the International Solar Alliance (ISA).The ISA which was jointly introduced in 2015 by France and India, aims to solve the issues of climate change and sustainable development.[26] India works with other International Solar Alliance (ISA) members to encourage the deployment of solar energy as one of the organization's founding members. The ISA works to increase the availability of renewable energy sources that are required for the generation of green hydrogen, even if its focus is not primarily on green hydrogen.[27]

In order to foster collaboration in the fields of renewable energy and hydrogen technologies, India has inked Memorandum of Understanding (MoUs) with a number of nations and international organizations. These agreements usually specify the areas of cooperation, including policy exchange, technology transfer, joint research, capacity building, and building on green hydrogen.[28] India actively participates in the IEA's(International Energy Agency) campaigns to support hydrogen and other clean energy transitions. To help member nations implement green hydrogen and other clean energy alternatives, the IEA offers a forum for exchanging best practices, policy insights, and technological know-how.

To work with other nations and industry stakeholders on advancing green hydrogen technologies and scaling up its production and use globally, India has joined international hydrogen coalitions and alliances, such as the Hydrogen Energy Ministerial Meeting (HEMM) and the Green Hydrogen Catapult initiative. The HEMM serves as a platform for high-level discussions among nations on projects, plans, and policies pertaining to hydrogen energy. India can interact with other countries to share best practices, exchange ideas, and work together on research and development projects targeted at improving hydrogen technology thanks to its membership in the HEMM. India can share its knowledge of innovative technologies and sustainable energy while learning from international experts in the hydrogen energy space by taking part in the HEMM.[29]

Green Hydrogen Catapult initiative: By 2025, top businesses and organizations worldwide will work together to increase the production of green H2 to a level that is competitive with conventional hydrogen in terms of cost. India's involvement in this program shows that it supports international industry partners and stakeholders in working together to accelerate the adoption of green hydrogen technologies. India may get access to capital, knowledge, and market opportunities through the Green Hydrogen Catapult initiative, hence expediting the development and implementation of green H2 projects both nationally and internationally.[30]

By engaging in global hydrogen coalitions and alliances such as the Green Hydrogen Catapult effort and HEMM, India can bolster its standing as a pivotal participant in the worldwide shift towards a low-carbon economy. These alliances give India great chances to work with foreign nations, businesses, and associations to get over financial, legal, and technical obstacles in the way of the mass adoption of green hydrogen and to meet its energy and climate targets.

India's commitment to international cooperation and collaboration in combating climate change and making the transition to a sustainable energy future is reflected in these agreements and partnerships. India's cooperation with other nations and international organizations is expected to increase as green hydrogen gains traction as a crucial element of the global energy transition, thereby propelling the development and deployment of green hydrogen technologies both nationally and internationally.

SUGGESTIONS

1. Policy Enhancement: Continuously refine policies to explicitly support the production and usage of green hydrogen. Ensure that regulatory frameworks provide clear incentives for investing in green hydrogen infrastructure and technology, while also imposing strict regulations on alternatives that are high in carbon emissions.
2. Mobilizing Investments: Encourage both domestic and international investment targeted specifically at projects related to green hydrogen. Facilitate partnerships between the public and private sectors to speed up the development of infrastructure, technology, and research initiatives related to green hydrogen.
3. Infrastructure Expansion: Give precedence to building infrastructure customized for the production, storage, and distribution of green hydrogen. Allocate resources towards expanding electrolysis plants, establishing hydrogen storage facilities, and creating dedicated transportation networks to facilitate the significant scaling up of green hydrogen production.
4. Promoting Technological Innovation: Foster efforts in research and development that focus on advancing technologies for green hydrogen production. Support collaboration with global leaders in hydrogen technology to benefit from their expertise and accelerate progress in reducing costs and enhancing efficiency.
5. Integration of Renewable Energy: Accelerate the implementation of renewable energy sources, particularly solar and wind power, to supply clean electricity for the production of green hydrogen. Formulate strategies that synchronize renewable energy projects with green hydrogen initiatives to guarantee a sustainable and carbon-neutral production process.
6. Building Capacity: Allocate resources towards training and educational programs aimed at cultivating a proficient workforce to bolster the expansion of the green hydrogen sector. Collaborate closely with academic institutions and industry stakeholders to bridge skill deficiencies and cultivate proficiency in green hydrogen technologies.
7. Enhance collaboration with other nations, international entities, and industry stakeholders: To facilitate the exchange of expertise, resources, and optimal methodologies concerning the production and application of green hydrogen. Participate actively in global coalitions and initiatives aimed at

fostering joint endeavours towards transitioning to an economy centered around hydrogen.

8. Campaigns for Public Awareness: Initiate focused awareness campaigns aimed at policymakers, businesses, and the general public to highlight the advantages and various uses of green hydrogen. Garner support for green hydrogen initiatives by underscoring its significance in meeting sustainability objectives and combating climate change.
9. Pilot Projects: Initiate projects in key sectors to demonstrate the viability and effectiveness of applications for green hydrogen. Use these projects to collect real- world data, identify challenges, and refine strategies for broader implementation of technologies related to green hydrogen.
10. Alignment of Incentive Mechanisms: Align incentive mechanisms such as subsidies, tax incentives, and carbon pricing with the specific requirements of production and use of green hydrogen. Design incentive schemes to stimulate demand for green hydrogen while also encouraging innovation and growth in the market for this sector.

By implementing these revised suggestions, India can leverage its potential in renewable energy and strategic partnerships to accelerate the transition to a green hydrogen economy. Focusing on targeted interventions that address the unique challenges and opportunities associated with green hydrogen will enable India to establish itself as a leader in sustainable energy production and make significant contributions to efforts in climate change mitigation.

CONCLUSION

In the realm of India's energy sector, a revolutionary transformation looms ahead, poised to usher in a new era of sustainability. At the very heart of this metamorphosis lies green hydrogen, poised to assume a pivotal role in shaping this profound journey. This research paper provides important insights and suggestions for achieving a thriving and sustainable green hydrogen ecosystem by thoroughly examining a number of aspects related to India's green hydrogen prospects.

First and foremost, it is clear that green hydrogen has enormous promise as a clean, adaptable energy source that can decarbonize a variety of economic sectors, including power generation, transportation, and industry. In light of India's aggressive climate targets and its dedication to cutting greenhouse gas emissions, green hydrogen presents a viable route to accomplishing these goals while maintaining energy security and promoting economic expansion. Policymakers can stimulate innovation in hydrogen generation, storage, and use technologies and the development of green hydrogen infrastructure by offering subsidies, encouraging investment, and enacting carbon pricing systems.

India's transition to green hydrogen will be accelerated in large part by foreign and domestic collaboration. India can accelerate the development of green hydrogen by collaborating with academic institutions, industry players, and other countries leading the way in this field. By doing so, it can pool resources, exchange best practices, and ease knowledge transfer. In summary, India is at a turning point in its pursuit of a sustainable energy future, and green hydrogen presents a strong case for addressing the interconnected issues of energy security, economic growth, and climate change. India has the potential to become a worldwide leader in green hydrogen innovation and create a more sustainable, wealthy, and environmentally friendly future for future generations by adopting the suggestions presented in this research paper and establishing a clear course of action.

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