Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Economic Viability of Green Hydrogen Vs. Other Renewable Energy Sources: A Legal Analysis

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The need to address climate change, improve energy security, and guarantee sustainable growth is causing a radical upheaval in the global energy sector. The progressive shift away from fossil fuels and toward renewable energy sources is what defines this transition, which has significant effects on the environment, economies, and communities. Through a legal perspective, this study compares the economic feasibility of green hydrogen to other renewable energy sources like solar, wind, and bioenergy.

With an emphasis on India's National Green Hydrogen Mission, this study examines the cost structures, scalability, and regulatory frameworks influencing the global adoption of green hydrogen. In addition to discussing legislative incentives and legal issues including land and water use, environmental compliance, and intellectual property rights in technology innovation, the analysis highlights important economic considerations like production costs, infrastructure needs, and market preparedness.

The potential of green hydrogen to aid in decarbonisation alongside more established renewables is examined in this research, which highlights the importance of strong legal and regulatory frameworks in promoting cost parity and deployment scaling. To increase green hydrogen's economic competitiveness in a constantly changing energy landscape, recommendations include harmonizing regulations, promoting international cooperation, and strengthening public and private partnerships.

Keywords: Green Hydrogen; Economic viability; Investments; Renewable energy; Legal study.

1. Introduction

As a robust buffer against the unpredictability of renewable energy sources, green hydrogen emerges as a crucial alternative for reducing their fluctuation. The goal of this research is to create the best possible green hydrogen system that can handle variations in the production of renewable energy, different patterns of hydrogen demand, and comparison with other renewable energy sources.

Using electricity, a chemical process known as electrolysis divides water molecules into hydrogen and oxygen. A power source that provides electricity, preferably from renewable sources like solar, wind, or hydropower, an electrolyte that facilitates the flow of ions within the system, electrodes that conduct electricity to start the chemical reaction, and a separator or membrane that permits ion exchange while preventing recombination of the produced hydrogen and oxygen gases are the main parts and steps of the process.

Zero carbon emissions are the first advantage of using green hydrogen. It is an eco-friendly solution because the process only releases oxygen as a by-product. Second, green hydrogen technology has a wide range of uses, including boosting fuel cell production, energizing industrial operations, and serving as a fuel for vehicles. Thirdly, this method solves the energy storage problem. In order to balance grid swings, extra renewable energy is stored in hydrogen. Last but not least, decarbonisation of the environment makes it possible for industries like heavy transportation, steel manufacturing, and ammonia production to operate carbon free.

2. Viability of Green Hydrogen Technology (GHT):

For more than a century, hydrogen has been recognized as a possible medium for energy storage. It can generate power by combustion in turbines that emit no carbon dioxide (CO2) or in fuel cells that only create water as a waste product. It has been demonstrated to be a feedstock for chemicals and fertilizers. However, the majority of hydrogen produced today comes from fossil fuels, which release billions of tons of carbon dioxide equivalent year.

For India, green hydrogen presents a home grown opportunity as it holds the promise, along with renewables, to lift the yoke of expensive energy imports from its economy, which is more than 230 billion dollars per year (19.1 trillion INR) for crude imports.

3. National Green Hydrogen Mission

The Indian government's flagship program, the National Green Hydrogen Mission, aims to help the nation's shift to a low carbon economy by encouraging the production, use, and export of green hydrogen and its by-products. In January 2023, it was formally introduced, costing Rs. 19,744 crores in total. By 2030, the government hopes to accomplish production of around 5 million metric ton (MMT) per year green hydrogen capacity. The Renewable Energy Capacity, specifically, for the generation of green hydrogen, shall add to around 125 GW of renewable energy capacity. The goal is to cut CO2 emissions by 50 million metric tons per year. The objective is to promote investment which can aid the government to raise Rs.8 lakh crore for production and development of green hydrogen. It will also aim to create jobs in various sectors which will amount to more than 6 lakh positions in the industry.

India's National Green Hydrogen Mission supports its pledge to meet the Paris Agreement's net zero emissions target by 2070. In order to establish India as a major exporter of green hydrogen to Europe, Japan, and other international markets, the project makes use of the nation's plentiful renewable energy resources, including solar and wind.

4. Cost Components in establishing Green Hydrogen Technology:

For green hydrogen technology to be widely adopted and competitive in India, its cost components and economic variables are crucial. The electrolysis process is the main cause of cost, with electricity making up between 60 and 70 percent of the entire cost of production. The availability and cost of renewable energy sources, such as wind and solar, have a big influence on the broader economy because of the dependence on them. Another significant element is the capital investment (CAPEX) required to build up electrolyser units and infrastructure, such as storage and transportation networks. Furthermore, the cost structure is increased by the development of auxiliary technologies like fuel cells and effective storage solutions.

Notwithstanding these obstacles, the National Green Hydrogen Mission's government incentives, economies of scale, and falling renewable energy tariffs are intended to significantly reduce costs. It is anticipated that the mission's emphasis on research and development, domestic production, and strong supply chains will make green hydrogen economically feasible and establish India as a world leader in this game changing technology.

4.1. Green Hydrogen Production Costs:

An important factor in establishing the economic feasibility of green hydrogen production is the cost of the electrolyser. These expenses consist of the electrolyser unit's installation and capital expenditure (CAPEX), as well as operating and maintenance expenses (OPEX) and energy usage.

If considered internationally, the cost of an electrolyser today varies according to its type and technology. The cost of using alkaline electrolysers ranges from $500 to $1,000 per kilowatt (kW). The price range for proton exchange membrane (PEM) electrolysers is from $700 to $1,400 per kW. Because of their effectiveness at high temperatures, Solid Oxide Electrolysers (SOEC) are a little more expensive but show promise. Due to early market development, limited domestic manufacturing, and reliance on imports, the cost is now higher in India.

5. Comparison with Other Renewable energy resources

5.1. Solar energy:

The cost of photovoltaic panels makes up between 40 and 50 percent of the overall system cost. PV modules in India cost between Rs.20 and Rs.30 per watt as of 2024, depending on the technology (e.g., thin film, polycrystalline, or monocrystalline). The cost of Module Efficiency increases with the efficiency of the modules (monocrystalline, for example), which are marginally more expensive but generate more energy per unit area. Around Rs.15 to Rs.20 per watt is the additional cost associated with the Balance of System (BOS), which consists of inverters, mounting structures, wiring, and other electrical components.

General upkeep, inverter service, and panel cleaning are all included in the operations and maintenance (O&M) costs of solar facilities. In India, yearly maintenance expenses for each MW range from Rs.3 to Rs.5 lakhs. Location specific considerations like dust levels (regular cleaning is required in arid locations) and long term inverter replacement costs since inverters usually last 8 to 10 years and have an impact on these maintenance expenses. Effective performance is ensured by routine maintenance, which normally keeps deterioration rates between 0.5 and 1% each year.

For intermittent renewable energy sources like solar, energy storage is crucial, particularly for the continual creation of hydrogen. The most popular are lithium ion batteries, which in India cost between Rs. 15,000 and Rs. 20,000 per kWh. The major amount of battery costs is related to cell and pack expenses.

5.2. Wind energy: Turbine installation, grid connectivity, and variability costs:

About 60–70% of the total project expenditures in India are related to the installation of wind turbines, which represents the highest portion of wind energy project expenses. This covers transportation, on site assembly, and the production and acquisition of turbines, which range in price from Rs.50 lakhs to Rs.1 crore per MW. Because they are less expensive to install than offshore wind turbines, which need sophisticated maritime engineering, onshore wind turbines are more prevalent in India. Furthermore, charges are largely influenced by the cost of acquiring land and preparing foundations, especially in high wind areas like Tamil Nadu, Gujarat, and Maharashtra. Larger rotor diameters and improvements in turbine technology are contributing to increased energy output and a decrease in the cost per unit of power produced.

In India, the cost of grid connectivity is extremely high, especially in areas where wind farms are situated distant from load hubs or cities. These expenses cover the construction of new substations, transmission lines, and grid integration for wind energy. By bolstering grid infrastructure and guaranteeing effective power evacuation from renewable energy installations, such as wind, the Indian Government’s Green Energy Corridor initiative seeks to alleviate these issues. Delays in grid development and connectivity, however, continue to be a problem and frequently result in project cost overruns.

Because wind generation is seasonal and dependent on regional wind patterns, wind energy in India has variable costs due to its intermittent nature. Investing in backup systems like thermal or hydroelectric facilities or storage options like batteries is necessary to manage these variations. In order to estimate wind energy availability and efficiently balance supply and demand, grid operators must also implement sophisticated forecasting tools. When actual power generation differs from projections, grid authorities impose deviation penalties and scheduling charges on wind power companies. Notwithstanding these obstacles, wind energy is becoming more affordable in India thanks to encouraging government regulations, competitive bidding, and technology developments, making it an essential part of the nation's renewable energy mix.

5.3. Bioenergy: Feedstock costs, processing technologies, and carbon implications:

Bioenergy offers both potential and challenges in India, with feedstock costs, processing technology, and carbon implications being the main cost factors. A sizable portion of the costs associated with producing bioenergy come from feedstock. India has a wealth of agricultural waste that can be turned into bioenergy, including wheat straw, sugarcane bagasse, and rice husk. However, gathering, moving, and processing these feedstocks can be expensive, particularly in isolated or rural locations with inadequate infrastructure. Availability, seasonality, and local market conditions all affect feedstock prices. Furthermore, sustainable sourcing of bioenergy feedstock is necessary to avoid adverse effects on soil quality or food production, which can further affect costs.

Overall costs are also impacted by processing technologies employed in the production of bioenergy, such as gasification, anaerobic digestion, and bioethanol synthesis. Biogas and biomass to electricity technologies are still in their infancy in India, despite the fact that the generation of bioethanol from sugarcane and agricultural waste has become more established. These technologies come with high operating costs for upkeep and improvement, as well as a large capital expenditure for facilities and equipment. The entire profitability and efficiency of bioenergy projects are impacted by the technology selection. For instance, biogas plants can be more affordable in rural areas where organic waste from homes and farms can be used, but larger scale biomass power plants need strong infrastructure for the distribution of energy and the acquisition of feedstock.

The effects of bioenergy on carbon in India are complicated. Despite being a renewable resource, bioenergy's carbon neutrality is dependent on a number of variables, such as the carbon emissions from the transportation, processing, and gathering of feedstock. Another important consideration is the feedstock's capacity to sequester carbon. Bioenergy can help reduce net carbon emissions if the feedstock comes from sustainable sources, including agricultural waste that would otherwise decompose and produce methane. However, it may result in higher carbon emissions if the feedstock is obtained through unsustainable methods like mono cropping or deforestation.

By encouraging sustainable bioenergy practices and providing incentives for carbon emission reducing technology, such second generation biofuels made from non-food feedstock, India is actively attempting to allay these worries. Furthermore, if properly managed, the incorporation of bioenergy into India's renewable energy mix might help the country achieve its climate goals by promoting a circular economy and offering a cleaner substitute for fossil fuels.

6. Levelized Cost of Energy (LCOE): Comparative analysis of LCOE across green hydrogen and other renewables.

The Levelized Cost of Energy (LCOE), which accounts for capital expenses, operating costs, and energy output, is a crucial indicator used to evaluate the cost effectiveness of energy generation technologies. It represents the cost of energy generated per unit over the course of an energy project. Regarding green hydrogen and other renewable energy sources, LCOE is essential in assessing the technologies' competitiveness and economic feasibility.

The cost of renewable electricity (mostly from solar or wind), the cost of the electrolyser, and the expenses of operation and maintenance all have an impact on the LCOE for green hydrogen. The LCOE for producing green hydrogen is comparatively high as of 2024; depending on the location and production scale, it usually ranges from Rs.300 to Rs.500 per kilogram of hydrogen. The capital intensive nature of electrolyser technology and the sporadic availability of renewable electricity are the main causes of this. The LCOE for green hydrogen is anticipated to drop considerably over the next ten years, though, as production increases, electrolyser costs come down, and the cost of renewable energy keeps going down.

Projections indicate that by 2030, the LCOE for green hydrogen could drop to Rs.150 to Rs.250 per kg, making it more competitive with fossil fuel-based hydrogen and helping it play a larger role in decarbonizing sectors like industry and transportation. Other renewable energy sources, including solar and wind, typically have LCOEs that are far lower. Thanks to competitive auctions, economies of scale, and falling costs for photovoltaic (PV) modules and wind turbines, the LCOE for solar energy in India has already reached Rs.1.8 to Rs.2.5 per kWh, while onshore wind can be as low as Rs.2 to Rs.3 per kWh. In their early phases, these renewable technologies offer a far lower LCOE than green hydrogen and are very effective at producing direct energy. When combined with storage devices, solar and wind energy can offer a dependable power source and are more economical for producing electricity.

It is evident from comparing the LCOE of green hydrogen with other renewable energy sources that, despite its current higher cost, it provides additional advantages. It can be used as a long term energy storage option for renewable energy, allowing the decarbonisation of hard to electrify industries like shipping, heavy industrial, and long distance transportation. It is anticipated that green hydrogen would become more cost competitive when compared to renewable energy sources like solar and wind as technology advances and it scales up, especially for applications that need variable fuel sources or energy storage.

7. Energy Efficiency: Energy losses in green hydrogen production vs. direct solar or wind usage.

Compared to using solar or wind energy directly, green hydrogen synthesis has far larger energy losses, which affects total efficiency and economic feasibility. Green hydrogen is produced by using electrolysers that convert water into hydrogen and oxygen using renewable electricity. This process has an efficiency of 60–80%, meaning that 20–40% of the energy is lost as heat. Ten to twenty percent more is lost during the compression, storage, and transportation of hydrogen. Only 30–40% of the initial energy is recovered if hydrogen is subsequently transformed back into electricity using fuel cells or turbines.

Direct solar or wind energy generation, on the other hand, requires less energy conversion and can achieve over 90% efficiency when transmitted and used through contemporary systems. For applications where direct electrification is practical, the higher energy losses of green hydrogen make direct renewable energy use more efficient, even though it has the advantage of energy storage and decarbonizing hard to electrify sectors.

8. Hydrogen (compression, liquefaction, pipelines) vs. battery storage for solar and wind energy.

Different strategies for storing solar and wind energy are provided by hydrogen and battery storage, each with special benefits and drawbacks. Compression (to pressures of 350 to 700 bar) and liquefaction (cooling to -253°C) are two processes involved in hydrogen storage, and depending on the technique, they both use 10 to 40% of the stored energy. Hydrogen transport pipelines are feasible for long distance, large scale energy distribution, but they come with additional infrastructure costs and energy losses. For short term and localized energy needs, however, battery storage, like lithium ion batteries, is significantly more energy efficient since it can store electricity directly with a round trip efficiency of 85 to 95%.

Batteries are less appropriate for seasonal or large scale storage due to their limitations in terms of energy density, cost, and deterioration over time. Batteries are ideal for instantaneous, high efficiency energy usage, but hydrogen is superior at storing energy for longer periods of time and in larger volumes, which makes it more appropriate for industrial applications and grid balancing over weeks or months. Both systems work well together; batteries allow for quick, short term energy deployment, while hydrogen solves long term storage issues.

9. Hydrogen as a long term storage solution vs. challenges in integrating variable renewable energy (VRE) like solar and wind

To overcome the difficulties of incorporating variable renewable energy (VRE) sources like solar and wind into energy networks, hydrogen presents a viable long term energy storage option. Because VRE generation is inherently intermittent and energy availability is influenced by time and weather, supply and demand are not aligned. By electrolyzing electricity to produce hydrogen, excess renewable energy can be stored during times of high generation. By using this stored hydrogen to generate fuel, heat, or electricity over the course of days, weeks, or even months, energy production can be successfully separated from immediate use.

There are still major obstacles to overcome, though. Compared to batteries, which have an overall efficiency of 85–95% for short term storage, the process of turning renewable electricity into hydrogen and back into useful energy involves energy losses, with an efficiency of 30–40%. Furthermore, hydrogen infrastructure, including fuel cells, storage tanks, pipelines, and electrolysers, necessitates significant upfront expenditures and technological developments. Complexity is further increased by safety issues relating to the flammability of hydrogen and the creation of strong restrictions.

Notwithstanding these difficulties, hydrogen is particularly well suited for long term storage and as a supplement to batteries in an energy mix that is dominated by renewables due to its high energy density and scalability. Hydrogen may be essential in resolving VRE integration problems, maintaining grid stability, and facilitating comprehensive decarbonisation across industries as costs come down and technology advances.

For green hydrogen to be widely used, its present $3–5 per kilogram (kg) price must drop dramatically. Green hydrogen will gradually replace fossil fuels as a clean alternative in many applications due to its falling manufacturing costs. Without a hefty carbon price, decarbonizing even the most difficult industries will be financially feasible at $1/kg, or $7.5 per million British thermal units of heat (MMBtu). Given that India lacks substantial proven sequestration deposits, making carbon capture and storage impractical, the feasibility of green hydrogen is especially pertinent to the country. Furthermore, excluding additional expenses for inland shipping, regasification, and other taxes, the price of imported liquefied natural gas has remained at or above 7.5 dollars/MMBtu for the previous ten years, making the nation susceptible to the dollar.

10. International policies:

Because of its potential to decarbonize businesses, provide energy security, and achieve climate targets, governments throughout the world are enacting regulatory measures to accelerate the development of green hydrogen. To build a strong hydrogen economy, these policies include financial incentives, regulatory frameworks, and calculated investments.

Other nations are joining the competition to become global hydrogen hubs, with the United States, Japan, Australia, and Germany spearheading the push.

With the goal of installing 40 GW of electrolyser capacity by 2030, the European Union (EU) has created the Hydrogen Strategy for a Climate-Neutral Europe and executed the Green Deal. In their national hydrogen policies, member nations such as France and Germany have allocated billions of euros in subsidies for infrastructure development, research and development, and green hydrogen initiatives. In order to guarantee openness in the production and trade of renewable hydrogen, the EU is also creating a certification program.

Japan has led the way in Asia, concentrating on hydrogen for transportation and electricity. Through collaborations with Australia and the Middle East, the nation has set lofty objectives to commercialize hydrogen technology and extend the hydrogen supply chain. With goals to become carbon neutral by 2050, South Korea is encouraging hydrogen powered automobiles, fuel cells, and industrial applications through its Hydrogen Economy Roadmap. $8 billion has been set aside by the US under the Bipartisan Infrastructure Law to create regional hydrogen hubs and provide incentives for the production of clean hydrogen under the Inflation Reduction Act (IRA). By taking these steps, the United States hopes to become a leader in green hydrogen innovation and lower manufacturing costs to less than $1 per kilogram over the next several decades.

Australia is becoming a significant supplier of green hydrogen in the Southern Hemisphere by utilizing its wealth of renewable resources. To fulfil their increasing demand, the nation's National Hydrogen Strategy lays out plans for massive hydrogen hubs and collaborations with nations like South Korea and Japan. Similarly, in order to diversify their economies and stay relevant in the global energy market, Middle Eastern countries like Saudi Arabia and the United Arab Emirates are making significant investments in hydrogen projects.

These international policy measures are creating a favourable environment for green hydrogen, driving down costs, and fostering collaboration among nations. By accelerating deployment and building global supply chains, these initiatives aim to establish green hydrogen as a cornerstone of the future energy system.

10.1. Other important policy changes are as follows:

Globally the importance of green hydrogen is rising in order to ensure sustainability within nation states. Not only this, even the policies require that the production of green hydrogen be connected to the production of renewable energy. By raising the cost of fossil fuels, carbon pricing schemes like the EU Emissions Trading System (ETS) encourage the switch to green hydrogen. Another imperative goal is to guarantee openness and trade conformity, European policies such as CertifHy are creating guidelines for green hydrogen certification. In order to create green hydrogen export chains, developed countries are partnering with resource rich nations (such as Saudi Arabia, Namibia, and Australia). Initiatives such as the European Hydrogen Backbone seek to create a network of transcontinental hydrogen pipelines. By combining the production, distribution, and storage of hydrogen within local economies, the EU promotes regional hydrogen valleys. Also, in order to increase electrolyser efficiency, governments are spending a lot of money on research and development.

11. Conclusion and Recommendation:

Innovation will also be important, especially in terms of increasing electrolyser efficiency. Investment will be made possible by a price premium made possible by a strict definition of green hydrogen and its derivatives with relation to the total permitted emissions. One positive move is the GH2 Green Hydrogen standard. Due to the early difficulties in transporting hydrogen, the early focus of commerce is probably going to be on derivatives like methanol and green ammonia. Additionally, being encouraged are hydrogen hubs, which are locations where green hydrogen and its by-products are produced, used, and exported.

When compared to other renewable energy sources, the economic feasibility of green hydrogen depends on a number of variables, such as market dynamics, regulatory frameworks, and technological developments. Green hydrogen has enormous potential as a flexible and sustainable energy source that can decarbonize industries like heavy industrial and long distance transportation where direct electrification might not be practical. The high capital costs of electrolysers, renewable energy generation, and infrastructure development, however, continue to pose a serious obstacle to its cost effectiveness. However, thanks to years of development and advantageous economies of scale, alternative renewable energy sources, such as solar, wind, and hydroelectric power, have become more cost competitive with fossil fuels.

Although green hydrogen has encouraging opportunities, ongoing advancements in production efficiency and storage capacity are necessary for its economic feasibility in comparison to other renewable energy sources. To promote worldwide trade and investment in green hydrogen, legal instruments must give equal weight to financial incentives as well as the creation of standardized international standards and certification programs. Ultimately, green hydrogen's contribution to the worldwide shift to a low carbon economy will depend on striking a balance between cost competitiveness and environmental sustainability.

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