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Research
Report

The economics of hydrogen production, distribution and storage

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Summary

The economics of hydrogen production, distribution, and storage encompass a critical area in the energy sector, particularly as global efforts intensify to address climate change and transition towards sustainable energy sources.

Hydrogen, recognized for its versatility and potential to decarbonize various sectors including transportation, industry, and power generation, has garnered significant attention and investment from governments and private entities worldwide. This interest is driven by the imperative to reduce greenhouse gas emissions and enhance energy security, as well as by technological advancements that have improved the feasibility and cost-effectiveness of hydrogen technologies.

Hydrogen production can be achieved through multiple methods, each with varying implications for environmental impact and economic viability. Traditional methods such as natural gas reforming dominate current hydrogen production due to their cost efficiency, although they are associated with carbon emissions.

In contrast, water electrolysis, especially when powered by renewable energy, offers a pathway to produce green hydrogen with minimal environmental impact, although it remains costlier and less efficient as of now. Emerging technologies and continuous innovation in electrolysis, fuel cells, and storage materials are crucial for driving down costs and achieving commercial viability.

The distribution and storage of hydrogen present additional economic and technical challenges. Efficient distribution systems, including pipelines and specialized transportation methods, are essential for connecting production sites with end-users.

Storage solutions, ranging from compressed gas and liquid hydrogen to advanced chemical and underground storage methods, are pivotal for ensuring a stable hydrogen supply and integrating it into existing energy systems.

The development of robust infrastructure and regulatory frameworks is vital to support the scaling up of hydrogen applications and mitigate issues such as leakage and safety concerns.

Market dynamics and governmental policies play a significant role in shaping the economics of hydrogen. Financial incentives, regulatory support, and international collaboration are crucial for fostering the growth of the hydrogen economy.

Governments are implementing various measures such as tax credits, public funding, and regulatory reforms to promote low-emission hydrogen production and remove barriers to market entry. However, the hydrogen sector also faces challenges

related to regulatory delays, high initial costs, and the need for substantial investment in research and development.

Overall, the hydrogen economy holds the promise of significant environmental and economic benefits, including the reduction of carbon emissions, enhancement of energy security, and creation of new markets and jobs.

Nevertheless, realizing this potential requires coordinated efforts across multiple sectors, continuous technological innovation, and comprehensive policy support to address the existing challenges and drive the transition towards a sustainable hydrogen future.

History

The history of hydrogen production, distribution, and storage can be traced back several decades, but significant advancements have been made in recent years due to heightened concerns over climate change and the push for decarbonization. Governments have started to make funding available to support the first large-scale projects, particularly in North America and Europe, which have taken the lead in implementing initiatives to encourage low-emission hydrogen production. Programs such as the US Hydrogen Production Tax Credit, the EU Important Projects of Common European Interest, and the UK Low Carbon Hydrogen Business Model are notable examples of these efforts[1].

Despite these initiatives, the lengthy time lags between the announcement of support schemes and the actual availability of funds have delayed project execution and even put some projects at risk. Additionally, the lack of regulatory clarity has only recently been addressed in certain jurisdictions, further complicating the process[1]
. The early 2020s have thus been a critical period for the hydrogen industry, marked by both challenges and opportunities. Technological advancements have played a crucial role in shaping the hydrogen market. Improvements in electrolysis, fuel cells, and storage materials have been essential in enhancing efficiency, durability, and cost-effectiveness[2]
. However, these technological advancements require continuous innovation and significant R&D investments to reach commercial viability. The next decade is expected to see strong demonstration efforts to ensure key hydrogen technologies achieve commercialization soon[3]
. Economic factors also influence the hydrogen market significantly. The economic viability of hydrogen applications is expected to increase as taxes or greenhouse gas emissions costs rise, and as barriers in infrastructure and availability of industrial-scale equipment are removed[4]

. The development and scaling up of the necessary equipment and processes to reduce the costs of hydrogen production, distribution, and development are crucial for the market's growth. Machinery manufacturers, in particular, have a pivotal role in this process, and companies are encouraged to innovate and develop technically superior and cost-efficient products to capture a significant market share[4]
. The period also saw the introduction of regulatory measures to support the hydrogen economy. Governments have been urged to remove regulatory barriers and improve regulatory processes, such as licensing and permitting, to shorten project lead times without compromising environmental standards and public consultation[5]
. These measures are vital for enabling infrastructure projects, including renewable generation capacities and CO2 transport and storage.

Hydrogen Production

Hydrogen can be produced from a variety of domestic resources, including fossil fuels, biomass, and water electrolysis using electricity. The environmental impact and energy efficiency of hydrogen largely depend on the method of production
[6]
. Hydrogen is commonly found in compounds such as water (H_2O) or methane (CH_4), and it must be separated into pure hydrogen (H_2) for use in various applications, such as fuel cell electric vehicles, where it combines with oxygen to generate electricity and water through an electrochemical process[7]
.

Natural Gas Reforming/Gasification

The most prevalent method for hydrogen production is natural gas reforming, which involves reacting natural gas with high-temperature steam to produce synthesis gas—a mixture of hydrogen, carbon monoxide, and a small amount of carbon dioxide
[7]
. The carbon monoxide is then reacted with water to produce additional hydrogen. This method is both the cheapest and most efficient, accounting for the majority of hydrogen produced annually in the United States[7]
. When combined with carbon capture and storage (CCS), this method can yield hydrogen with lower carbon dioxide emissions. A similar process, called gasification, involves reacting coal or biomass with high-temperature steam and oxygen in a pressurized gasifier. This converts the coal or biomass into synthesis gas containing hydrogen and carbon monoxide, which can then be separated[7]
.

Water Electrolysis

Water electrolysis involves using electricity to split water into hydrogen and oxygen. Despite its potential for producing clean hydrogen, as of 2020, less than 0.1% of hydrogen production is derived from water electrolysis due to high costs and lower efficiency compared to natural gas reforming[8]. Conventional alkaline electrolysis has an efficiency of about 70%, but advanced alkaline water electrolyzers can achieve up to 82% efficiency[8]. Future projections estimate that the electrical efficiency of electrolysis could reach 82–86% by 2030[8].

High-Pressure Electrolysis

High-pressure electrolysis, which uses electricity produced by photovoltaic systems, offers one of the cleanest methods for hydrogen production. This involves breaking water into hydrogen and oxygen via a photoelectrochemical cell (PEC), a process also known as artificial photosynthesis[8].

Photobiological and Photoelectrochemical Water Splitting

Photobiological water splitting uses microbes, such as green algae, which consume water in the presence of sunlight and produce hydrogen as a byproduct[7]. Photoelectrochemical systems, on the other hand, employ special semiconductors and solar energy to produce hydrogen from water[7].

Hydrogen from Biomass

Biomass can be converted into syngas through gasification, which is further converted into hydrogen by a water-gas shift reaction (WGSR)[8]. This method is included under the broader category of green hydrogen production, which also covers hydrogen produced from renewable electricity via electrolysis.

Byproduct Hydrogen

The industrial production of chlorine and caustic soda by electrolysis generates significant amounts of hydrogen as a byproduct. This hydrogen can be cooled, compressed, and purified for use in other processes or sold via pipelines, cylinders, or trucks[8].

Thermochemical Cycles

Thermochemical cycles use heat sources in combination with chemical reactions to split water into hydrogen and oxygen. If electricity is also used, the cycle is referred to as a hybrid thermochemical cycle[8].

Current and Future Trends

TBD

Hydrogen Distribution

Hydrogen distribution involves the delivery of hydrogen from its production site to the location where it is consumed. This process encompasses various methods and infrastructure, tailored to the specific needs and consumption rates of different regions and industries.

Pipelines

Hydrogen pipelines are a prevalent method for distributing hydrogen, especially in areas with constant or substantial demand anticipated to persist in the future [9]. The hydrogen distribution system typically consists of a network of vital pipelines operating at varied pressures and hydrogen concentrations. These pipelines are integrated with composition and recycle compressors that propel the hydrogen through a complex system of consumer entities, manufacturing divisions, and platforming sections [9].

Storage Methods

Hydrogen can be stored and transported in multiple forms, classified mainly into compressed gas, cold compressed liquid gas, and hydrogen stored on or within solids [9].

Compressed Gas Storage

Compressed hydrogen gas is stored in high-pressure tanks, typically between 350 and 700 bar, depending on the application. This method offers high energy density and is suitable for stationary applications, refueling stations, and industrial use. However, it requires strong and lightweight tanks to withstand high pressures, and the compression and decompression processes result in energy losses[10][2].

Liquid Hydrogen Storage

Liquid hydrogen storage involves cooling hydrogen to extremely low temperatures to store it as a liquid. This method is energy-intensive due to the cooling requirements. Liquid hydrogen storage is mainly used where high storage densities are needed but

comes with significant energy losses due to boil-off and the energy required for liquefaction
[6]
.

Chemical Hydrogen Storage

Chemical storage methods involve storing hydrogen in chemical compounds that can release hydrogen when needed. Examples include metal hydrides and chemical hydrides. Metal hydrides absorb hydrogen gas and release it upon heating, while chemical hydrides store hydrogen in the form of a chemical compound and release it through various reactions. These methods offer high storage densities and can potentially overcome the challenges of compression and liquefaction, though they require additional processes for hydrogen extraction and regeneration
[10]
[9]
.

Underground Storage

Underground storage options include salt caverns, depleted natural gas reservoirs, and aquifers. Hydrogen can be injected and stored in these geological formations, offering large-scale storage capacities that can balance seasonal variations in hydrogen demand. However, site-specific geological considerations, containment integrity, and safety measures must be carefully evaluated for underground storage
[6]
[2]
[11]
[12]
.

Impact of COVID-19

The COVID-19 pandemic has affected the hydrogen market by restricting its growth. Despite this, hydrogen can still be accumulated in both vapor and liquefied states, although each state requires specific conditions for storage. Vapor state storage necessitates high pressure, whereas liquefied hydrogen storage demands subfreezing temperatures due to hydrogen's extremely low boiling point at one atmosphere pressure
[9]
.

Transportation

Hydrogen transportation involves moving hydrogen from its production site to the consumption area. This can be achieved through pipelines and on-road subfreezing liquid tankers [9].

Vision for the Future

The future vision for hydrogen transportation is extensive, aiming to power hundreds of millions of vehicles, including cars, trucks, buses, passenger ships, and locomotives. Hydrogen-based fuels could also power a significant share of airplanes and freight ships. Additionally, hydrogen could provide around 10% of the heat and power required for global households and industry sectors, contributing significantly to reducing CO2 emissions. For instance, the Hydrogen Council estimates that hydrogen deployment could avoid around 6 gigatonnes of CO2 annually by 2050, with half of the avoided emissions coming from transport sector applications [13].

Emissions and Leakage

However, hydrogen distribution is not without its challenges. Emissions and leakage throughout the value chain are significant concerns. Research indicates that loss rates from electrolyzers could be high, and the transportation of hydrogen might be a major source of emissions. Fluid dynamics theory suggests that hydrogen can leak 1.3 to 3 times faster than methane. Although recent studies have indicated that methane and hydrogen may leak at similar rates through low-pressure distribution pipes, high emission rates from liquified hydrogen due to boil-off are also a concern [13].

Hydrogen Storage

Hydrogen storage is a critical component in the hydrogen energy value chain, enabling the decoupling of hydrogen production from its supply and use. Effective storage solutions are necessary to secure a stable hydrogen supply for end-users, such as industry clusters, and to facilitate the creation of a global hydrogen market [14].

Storage Methods

There are several methods for hydrogen storage, each with its advantages and challenges:

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[6]
[2]

[11]
[12]
.

Technological Advancements

Advancements in hydrogen storage technologies are essential to address the challenges of storage capacity, safety, and cost-effectiveness. Researchers are exploring advanced materials such as metal hydrides, carbon-based materials, metal-organic frameworks (MOFs), and nanomaterials to enhance storage capacity, kinetics, and safety
[6]
. Improvements in storage technologies will play a crucial role in meeting future infrastructure requirements for hydrogen refueling stations, industrial facilities, and distributed power generation[2]
[9]
.

Safety Considerations

Hydrogen storage poses unique safety challenges due to its high flammability and potential for embrittlement. Ensuring the safety of hydrogen storage systems requires the development and implementation of stringent safety regulations, protocols, and public awareness programs. Governments, industry associations, and international organizations must collaborate to establish comprehensive safety guidelines and standards for hydrogen infrastructure, ensuring uniform safety protocols worldwide
[10]
[2]
.

Market and Economic Impacts

The hydrogen market is influenced by various competitive developments including sales contracts, agreements, investments, expansions, product launches, alliances, mergers, partnerships, joint ventures, collaborations, and acquisitions
[15]
. Governments play a crucial role in this market by implementing interventions such as loan guarantees, export credit facilities, and public equity investments to help developers manage increases in equipment and capital costs[1]
. Advanced economies are encouraged to raise concessional finance and enhance cooperation to develop first-of-a-kind projects in emerging markets and developing

economies. This could include the rapid standardization of contract templates to ease the unfamiliarity of parties with the new sector[1]
. Inflation, falling fossil fuel prices, and slow policy implementation have exacerbated the challenges in this sector, necessitating comprehensive government action across the whole value chain to prevent cancellations and setbacks[1]
. Hydrogen production costs are anticipated to increase post-2030 due to heightened demand, compelling production even under less favorable conditions[16]
. Currently, production costs are highest in Europe, but the Middle East and Africa (MEA) show the most significant future cost reductions, driven by expected lower energy costs[16]
. Future hydrogen production costs have a wide forecast range, from 0.36 to over 10 € per kg by 2050, highlighting the necessity for thorough review studies to understand these predictions better[16]
. Decarbonizing global hydrogen production can lead to both co-benefits and trade-offs with other impact categories. For instance, scenarios indicate a decrease in particulate matter, ozone depletion, and fossil resource depletion due to a shift from fossil fuels to renewable electricity. However, particulate matter emissions may initially rise due to slower transitions, and ozone depletion could slightly increase with higher natural gas-based power usage[17]
. In terms of regional dominance, North America leads in hydrogen storage and distribution technology, bolstered by the largest market for hydrogen generation, an increase in fuel cell-based electrical automobiles, and numerous hydrogen-based refineries[9]
. Key market players focus on raising awareness and promoting hydrogen applications to minimize emissions from various manufacturing processes, which in turn broadens their consumer base and increases sales[9]
.

Environmental and Social Impact

The environmental and social impact of hydrogen production, distribution, and storage is a multifaceted issue that encompasses a wide range of considerations.

Greenhouse Gas Emissions

One of the most pressing concerns is the environmental impact of hydrogen production methods. While hydrogen can be produced through various means, the method chosen has significant implications for greenhouse gas (GHG) emissions. For instance, hydrogen produced via natural gas steam methane reforming (SMR) with carbon capture and storage (CCS) still results in some GHG emissions due to fuel consumption and direct emissions. In contrast, hydrogen produced via water electrolysis using renewable electricity has the potential to achieve much lower GHG emissions [2]. The International Panel on Climate Change (IPCC) provides characterization factors to quantify global warming potentials, including the indirect impact of hydrogen leakages, which act as a secondary greenhouse gas [17].

Environmental Indicators

Beyond GHG emissions, hydrogen production impacts a variety of environmental indicators. These include acidification, freshwater ecotoxicity, resource use (energy carriers), eutrophication (aquatic freshwater, aquatic marine, terrestrial), human toxicity (cancer and non-cancer effects), ionizing radiation, land use, and ozone depletion [17]. Each of these factors needs careful consideration to fully understand the environmental footprint of hydrogen technologies.

Energy Security and Geopolitical Implications

The transition from fossil fuels to hydrogen and other renewable energy sources also has implications for energy security. Many countries currently depend heavily on imported fossil fuels, making them susceptible to price fluctuations and geopolitical tensions. By diversifying energy sources and increasing the share of domestically produced hydrogen, countries can reduce their dependence on imported fuels and enhance their energy security [2].

Social Perception and Public Awareness

Public acceptance and awareness are critical for the successful deployment of hydrogen energy. Misconceptions and lack of knowledge about the benefits and safety of hydrogen can hinder its acceptance. Governments and industry stakeholders must implement public awareness campaigns, education programs, and community engagement initiatives to address these misconceptions and promote understanding [2]. Public perception of hydrogen safety and its potential as a fuel source can be improved through these targeted efforts.

Safety Standards and International Cooperation

Ensuring the safety of hydrogen production, storage, and distribution is of paramount importance. Collaboration among governments, industry associations, and international organizations is necessary to develop comprehensive safety guidelines, standards, and best practices for hydrogen infrastructure. Harmonizing these safety protocols worldwide through international cooperation can facilitate knowledge sharing, technology transfer, and cross-border hydrogen trade [2].

Challenges in Storage and Distribution

Efficient storage and distribution of hydrogen are essential for its widespread adoption. Hydrogen's low energy density necessitates specialized storage methods, such as compressed gas storage and cryogenic liquid storage, each with its own set of challenges. Additionally, establishing a reliable and widespread hydrogen distribution infrastructure, including pipelines and refueling stations, requires significant investment. Future projections highlight the need for large-scale storage solutions to accommodate the intermittent nature of renewable energy sources [2].

[2] Promote public awareness and acceptance: public acceptance and awareness of hydrogen energy are key drivers for its successful deployment.

Technological Innovations and Research

Technological advancements play a crucial role in reducing the costs and increasing the efficiency of hydrogen production, distribution, and storage. A concerted effort towards innovation is essential to drive down costs and enhance the competitiveness of hydrogen technologies. This includes substantial increases in R&D budgets and support for demonstration projects to ensure critical hydrogen technologies reach commercialisation swiftly [3]. Much faster adoption of low-carbon hydrogen is imperative to align with global sustainable energy goals by 2050. The development of a global hydrogen market is essential for countries with limited domestic supply potential, providing export opportunities for those with substantial renewable or CO2 storage capabilities. Accelerated innovation efforts are needed as several critical hydrogen technologies remain in early development stages[3].

Research and Development

Continuous innovation is necessary to improve hydrogen technologies such as electrolysis, fuel cells, and storage materials. These improvements are needed to enhance efficiency, durability, and cost-effectiveness while ensuring safety considerations to build public confidence and secure safe handling, storage, and distribution of hydrogen
[2]
. There is an estimated need for USD 90 billion in public funding globally to support clean energy innovation, with about half directed towards hydrogen-related technologies[3]
.

Production Technologies

Hydrogen can be produced using various technologies, each with different efficiencies and environmental impacts. Key technologies include Coal Gasification (CG) with and without Carbon Capture and Storage (CCS), where coal is partially oxidized at high temperatures and pressures to produce a syngas mixture. This syngas undergoes a water-gas shift reaction to enhance hydrogen yield
[17]
. Technological improvements are also measured by the "learning curve rate," which represents cost reductions with each doubling of production capacity. Conservative estimates assume a 12% learning curve rate for green hydrogen technologies, although other studies suggest rates as high as 18% to 20%[11]
.

International Collaboration

Stronger international cooperation is identified as a key lever for the success of hydrogen innovation and market development. Collaborative efforts can significantly enhance the pace of technological advancements and market penetration, ensuring that innovations in hydrogen technologies meet the diverse needs of stakeholders globally
[3]
. This includes interdisciplinary research initiatives that bring together various sectors to support rapid and widespread industrial decarbonization[18]
.

Scaling and Cost Reduction

Scaling production capacity plays a vital role in reducing costs and improving the efficiency of hydrogen technologies. For instance, scaling up the balance of plant (BOP) components such as gas processing, cooling, and power supplies can significantly reduce operational costs

[19]
. A tenfold increase in installed capacity is expected to improve BOP costs by approximately $60/kW, while a hundredfold increase could yield improvements of up to $80/kW[19]
.