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Germany's Green Hydrogen Transition: Ambitions, Realities and Economic Barriers

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Abstract

Green hydrogen is a key component of Germany's strategy for a sustainable energy transition, which aims to significantly reduce carbon emissions by 2050. Germany relies heavily on it as a fundamental part of its energy transformation and has set ambitious targets for its production and imports. However, despite progress in green hydrogen production, gray hydrogen remains dominant in German industry, reflecting the economic and technological challenges Germany faces in this area. Among the most significant challenges are the high cost of green hydrogen compared to other hydrogen types and the lack of a sophisticated infrastructure for its distribution and storage. Nevertheless, Germany is striving to expand the use of green hydrogen by investing in numerous projects and supporting research and development in electrolysis technologies.

Keywords: *Green Hydrogen, Renewable Energy, Germany.*

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Introduction

With increasing environmental challenges and radical transformations in the global energy sector, the search for clean and sustainable energy solutions has become an urgent necessity. In this context, green hydrogen stands out as one of the promising alternatives to achieve an energy transition and reduce dependence on fossil fuels. Green hydrogen is produced through the electrolysis of water using renewable energy, making it zero carbon emissions and supportive of the Sustainable Development Goals.

Germany is one of the world's leading countries in adopting ambitious policies and strategies to invest in green hydrogen, as it seeks to strengthen its role as a global leader in this field. The German experience offers an important model for understanding how green hydrogen can contribute to a clean energy future. Despite the great potential that this sector offers, it faces a set of economic, technical, and political challenges that may hinder the achievement of its goals. Hence the importance of this research, which aims to study the opportunities and challenges associated with investing in green hydrogen, focusing on the German experience.

The main problematic: How Can Germany balance the promising opportunities and complex challenges of investing in green hydrogen, while striving for a sustainable energy transition.

Green hydrogen: concept, importance and uses:

The Concept of Green Hydrogen:

Green hydrogen is a type of hydrogen produced using renewable energy sources such as solar or wind energy. It is obtained through the process of electrolysis of water (Electrolysis), in which clean electricity is used to separate water (H2O) into its two main components: oxygen and hydrogen. This produces hydrogen

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without any carbon emissions, which makes it "environmentally friendly"(Agrawal, Mahajan, Singh, & Sreedhar, 2024).

The production mechanism of green hydrogen begins with the utilization of electricity generated from renewable sources, such as solar or wind power. This carbon-free energy is directed into an electrolyzer, where it drives the electrochemical dissociation of water, splitting the molecules into their constituent parts: hydrogen and oxygen. Following this separation, the resulting hydrogen is captured and stored, thereby becoming available for subsequent deployment as a clean fuel or as a feedstock for various industrial applications (Abudureyimu, Tuluhong, Chang, Wang, & Luo, 2025) .

The difference between green hydrogen and other types of hydrogen see (Abudureyimu et al., 2025).

Table.01: The difference between Green Hydrogen and other types of hydrogen

Type of hydrogen	How to produce	Emissions
Green hydrogen	It is produced by electrolysis using renewable energy	There are no carbon emissions
Gray hydrogen	It is produced from fossil fuels (such as natural gas) via the steam reforming process	It releases large amounts of CO2
Blue hydrogen	Similar to gray, but uses carbon capture and storage technology to reduce emissions	Relatively low emissions

Green hydrogen is distinguished from Gray and blue by the fact that it is completely based on clean energy sources and does not cause any environmental pollution, which makes it the most sustainable option for achieving climate goals. (See:(Scovell & Walton, 2024; Yu, Wang, & Vredenburg, 2021))

The Importance of Green Hydrogen in Achieving Sustainable Development:

Reducing Carbon Emissions:

Green hydrogen constitutes a carbon-free energy source that offers a viable alternative to fossil fuels, thereby playing a pivotal role in global decarbonization strategies. Its versatility allows for deployment across critical sectors: in energy systems, it enables zero-emission electricity generation and storage; in heavy industry, it substitutes carbon-intensive feedstocks such as coal and natural gas; and in the transportation sector, it functions as a clean fuel for hydrogen fuel cell electric vehicles (FCEVs). Ultimately, the widespread substitution of conventional pollutants with green hydrogen holds the potential to significantly curtail greenhouse gas emissions, directly contributing to the mitigation of climate change. (See: (Elshafei & Mansour, 2023; Patnaik, Pattanaik, Bagal, & Rath, 2023))

Relation To Renewable Energy and the Circular Economy:

The production of green hydrogen is intrinsically linked to the expansion of renewable energy infrastructures, as it relies exclusively on carbon-free sources such as solar and wind power. This dependency not only incentivizes the accelerated deployment of renewable technologies but also mitigates reliance on fossil fuels by offering a method to store and transport clean energy. Consequently, green hydrogen enhances the overall integration of renewables into the global energy mix, addressing the intermittency challenges often associated with variable renewable generation. (Federal Ministry for Economic Affairs and Energy, 2020(Oliveira, Beswick, & Yan, 2021))

Furthermore, green hydrogen plays a fundamental role in advancing the circular economy by promoting resource efficiency and minimizing waste. It functions as a critical "sector coupler" that bridges the gap between energy production, storage, and end-use applications. By enabling the conversion of surplus renewable electricity into a storable chemical vector that can be circulated and reused across various industries without degradation of value, green hydrogen facilitates the development of a more sustainable,

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closed-loop energy system. (See: European Hydrogen Observatory. (2023). Green Hydrogen Organisation. (2023)).

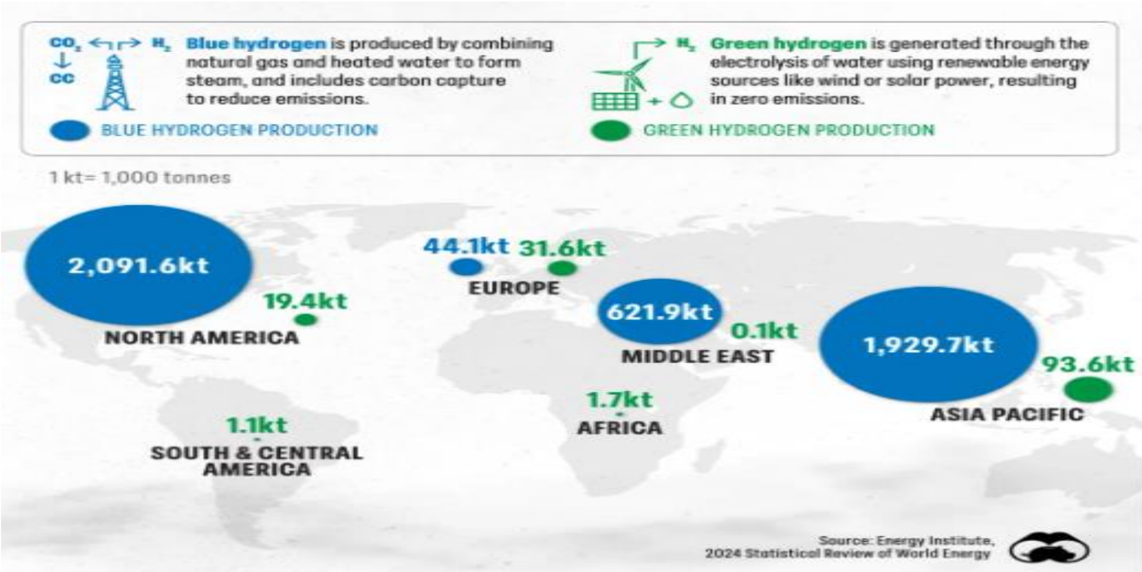

Figure01: Global hydrogen production in 2023

Source : wood Mackenzie (2024), Global Hydrogen Production by Region in 2023, Retrieved from: https://bit.ly/49ro4ok

Blue hydrogen production is currently more widespread than green hydrogen production because it relies on existing natural gas infrastructure, making it easier and less expensive. The higher cost of green hydrogen is primarily due to the high cost of renewable energy required for electrolysis, as well as current limitations in the technology. The electrolysis process itself is also energy-intensive, further contributing to the overall cost increase (see: (Durakovic, del Granado, & Tomasgard, 2023; Webb, Longden, Boulaire, Gono, & Wilson, 2023)).

Uses of Green Hydrogen:

In the transportation sector, green hydrogen serves as a critical fuel source for Fuel Cell Electric Vehicles (FCEVs), offering a decarbonized solution for mobility. It represents a viable alternative to conventional fossil fuels, such as diesel and gasoline, particularly within heavy-duty and long-haul applications including buses, freight trucks, rail systems, and aviation, where high energy density is required. Furthermore, hydrogen fuel cell technology addresses significant limitations associated with battery electric vehicles (BEVs); specifically, it provides the operational advantages of rapid refueling times and extended driving ranges, making it capable of meeting the rigorous demands of commercial logistics and mass transit with zero tailpipe emissions.(see:(Angelico, Giametta, Bianchi, & Catalano, 2025; Chakraborty et al., 2022; Osman, 2024))

Within the industrial domain, green hydrogen is instrumental in decarbonizing "hard-to-abate" heavy industries that cannot be easily electrified. In steel manufacturing, for instance, it functions as a clean reducing agent, replacing coal or coke in blast furnaces to produce "green steel." Additionally, it is essential for the synthesis of green ammonia, providing a sustainable feedstock for the fertilizer industry. The utility of green hydrogen also extends to oil refining and petrochemical processes, where its adoption aids in significantly mitigating the carbon footprint of chemical production and fuel processing. (see: (Cheekatamarla, 2024; Franco & Giovannini, 2023; Reda, Elzamar, AlFazzani, & Ezzat, 2024))

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In the broader energy sector, green hydrogen acts as a pivotal intermediary for energy storage and grid management. It addresses the intermittency challenges of renewable energy sources by absorbing surplus electricity generated during peak solar or wind conditions. This stored hydrogen can subsequently be utilized in power generation plants or reconverted into electricity during periods of low renewable output or high demand. A primary advantage of this approach over conventional electrochemical batteries is the capacity for long-duration and seasonal energy storage, which is essential for maintaining grid stability in a renewable-heavy energy system. (see: (Al-Hussein, 2025; bin Jumah, 2024; Marouani et al., 2023))

Finally, the strategic adoption of green hydrogen offers significant potential for enhancing national energy independence and security. By enabling the domestic production and storage of energy derived from local renewable resources, nations can substantially reduce their reliance on imported fossil fuels and exposure to volatile global energy markets. This shift not only strengthens energy security but also allows countries with abundant solar and wind resources to capitalize on their natural assets, fostering a self-sufficient and resilient energy infrastructure. (see: (Eicke, 2025; Mrozowski & Bednarz, 2023))

Green Hydrogen in Germany: Policy, Challenges and Opportunities:

The German Government's Policy of Supporting Green Hydrogen:

In 2020, the German government promulgated the "National Hydrogen Strategy," a comprehensive framework designed to accelerate the production and utilization of green hydrogen in alignment with the national goal of achieving carbon neutrality by 2045. This strategy establishes ambitious quantitative targets, most notably the objective to install 5 gigawatts (GW) of green hydrogen production capacity by 2030, with a subsequent expansion plan to reach 10 GW by 2040. Beyond production capacity, the strategy prioritizes the promotion of innovation and scientific research to refine electrolysis technologies and reduce associated costs, alongside the expansion of transport and storage infrastructure to facilitate cross-sector integration. Fundamentally, these measures aim to reduce the nation's reliance on fossil fuels, bolster Germany's economic competitiveness in the clean energy sector, and support the sustainable transformation of the industrial, transport, and energy sectors. (see: (Tholen et al., 2021))

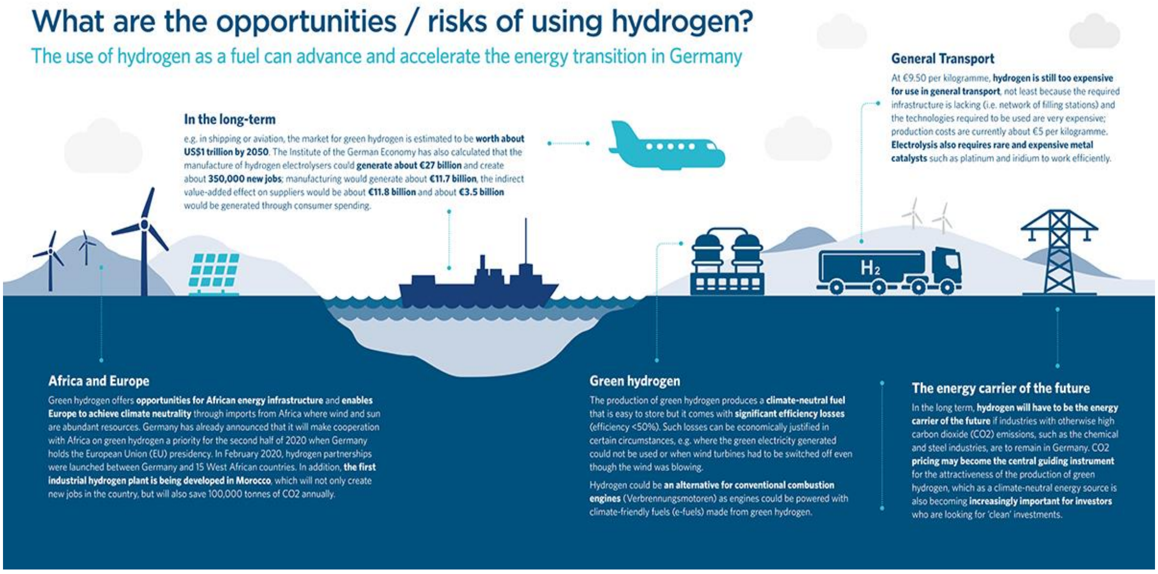

Figure02 : USE OF HYDROGEN IN GERMANY

Source : Herbert Smith Freehills Kramer LLP (September 22 2020), Hydrogen in Germany, Retrieved from: https://bit.ly/3N2oR7G

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To operationalize the National Hydrogen Strategy, the German government has committed a substantial fiscal package totaling approximately 9 billion euros. This funding is strategically allocated, with 7 billion euros designated to support domestic green hydrogen production projects, while the remaining 2 billion euros are reserved for strengthening international cooperation and developing joint ventures with partner nations. The government employs various mechanisms to deploy these funds, including tax incentives and direct subsidies for companies adopting green hydrogen solutions, as well as robust support for research and development in production and storage technologies. Furthermore, significant financing is directed toward Important Projects of Common European Interest (IPCEI) to foster regional collaboration within the European Union. Practical examples of these investments include the establishment of pilot projects and production plants in northern Germany, specifically targeted at decarbonizing heavy industries such as steel manufacturing and chemical production.(Quitzow, Nunez, & Marian, 2024)

Germany is currently developing a sophisticated infrastructure for green hydrogen, characterized by advanced production facilities that utilize electrolysis powered by renewable energy. A prominent example of this infrastructure is the "REFHYNE project" located in Cologne, which stands as one of Europe's largest green hydrogen production plants with a capacity of 10 megawatts (MW). Additionally, Germany is leveraging its geographic advantages by developing projects in the North Sea and the Baltic Sea, where hydrogen production is powered directly by offshore wind energy. The future trajectory of this infrastructure involves the construction of additional plants co-located with renewable energy sources, particularly in northern Germany, alongside the continuous development of new technologies aimed at increasing electrolytic efficiency and minimizing production costs .(See: European Commission (2020), (Cerniauskas, 2021))

Germany unveiled its hydrogen strategy in mid-2020 during the administration of then-chancellor Angela Merkel. This strategy included a thorough evaluation and potential update after three years. Additionally, the new coalition government, comprising the Social Democrats (SPD), the Green Party, and the Free Democrats (FDP), committed to an "ambitious update" to position the country as a leading player in hydrogen technologies by 2030. (Green Hydrogen Organisation,2024)

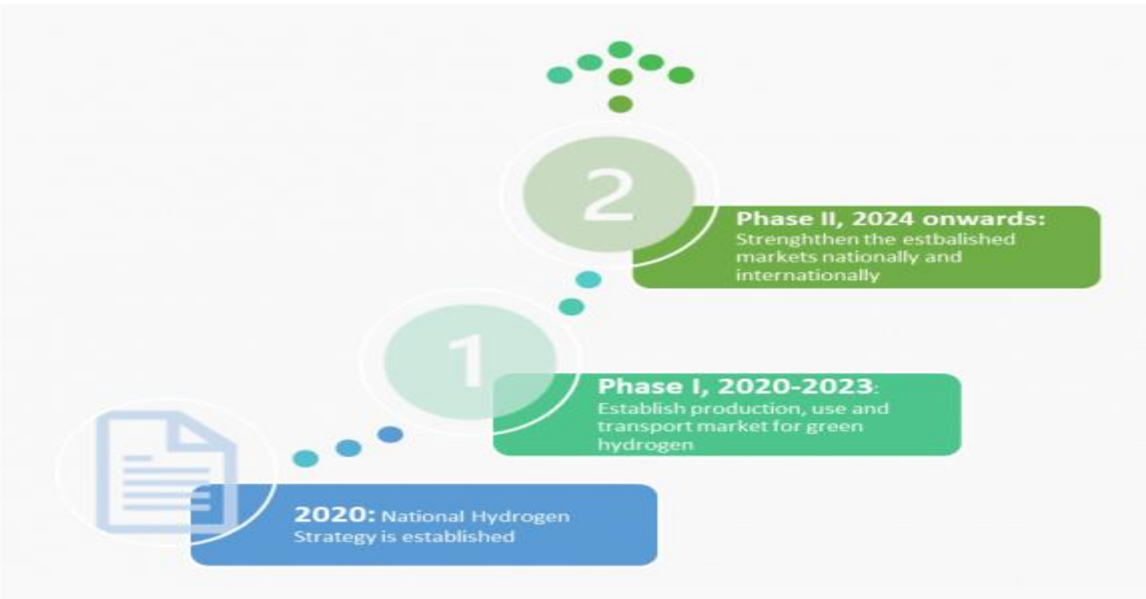

Figure 03: National strategy of Germany

Source: Green Hydrogen Organisation (GH2) (2024). GH2 Country Portal – Germany, Retrieved from: https://gh2.org/countries/Germany

Germany is actively developing a sophisticated hydrogen transport infrastructure, strategically leveraging its existing natural gas networks through extensive retrofitting and adaptation measures. This logistical

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framework involves the rehabilitation and expansion of legacy pipelines to accommodate hydrogen specifications, alongside the construction of dedicated transport networks that connect major industrial hubs. A prime example of this infrastructural evolution is the "HyPerLink" project, designed to establish a vital connection between hydrogen production sites in northern Germany and consumption centers in the south. Furthermore, Germany is collaborating with neighboring nations to establish cross-border corridors, thereby integrating its network into a broader European hydrogen grid. In terms of storage, the strategy capitalizes on geological assets, employing salt caverns for the subterranean storage of large-scale hydrogen reserves. Complementing this geological approach is the development of advanced technological solutions, including high-pressure tanks and liquid hydrogen storage systems, to ensure supply stability.(Clean Hydrogen, 2022)

Major corporations are assuming a pivotal role in the advancement of Germany's green hydrogen market, driving progress through significant capital investment and technological innovation (IEA, 2024). This sector is characterized by a synergistic partnership where the government provides necessary financial and regulatory frameworks, while private entities execute technological deployment and project implementation. Prominent industry leaders illustrate this dynamic: Siemens Energy is instrumental in developing advanced electrolysis technologies to enhance production efficiency (Widlund & Erlandsson Jonsson, 2025); Thyssenkrupp is spearheading the application of hydrogen in heavy industry, particularly in green steel production; and Linde specializes in the engineering of production plants and distribution networks. To further this collaboration, joint innovation centers are being established to devise novel solutions for hydrogen storage, transport, and utilization.

Recognizing the limitations of domestic production capacity, Germany seeks to strengthen international cooperation to facilitate the global production and trade of green hydrogen. The government has initiated several strategic bilateral partnerships to secure stable energy supplies and foster a global hydrogen economy. Notable examples include cooperation with Morocco on the "Power-to-X" project, which utilizes solar energy to produce hydrogen for export to Europe; agreements with Norway to import green hydrogen derived from offshore wind; and partnerships with Arab Gulf states to support production projects destined for European markets. These international alliances are critical not only for ensuring Germany's energy security and reducing production costs through global scale but also for supporting developing nations in their transition toward clean energy systems. (Green Hydrogen Organisation, 2024)

The Challenges of Investing in Green Hydrogen in Germany:

Technical challenges :

The production of green hydrogen is currently characterized by significant economic and technical complexities relative to gray or blue alternatives. The primary cost driver is the electrolysis process, which is energy-intensive and necessitates vast quantities of renewable electricity to separate water into its constituent elements. Although renewable energy costs are on a downward trajectory, the requirement for consistent, high-volume renewable power remains a binding constraint. Furthermore, the establishment of production infrastructure involves substantial capital expenditure due to the need for advanced, high-cost equipment. (Prabhu 2025) These challenges are compounded by logistics; transporting hydrogen over long distances via pipelines or tankers incurs additional costs necessitated by extreme compression or liquefaction processes. Moreover, technical inefficiencies, specifically energy losses during transport, represent a critical obstacle requiring innovative engineering solutions.

A critical technical barrier to the widespread adoption of green hydrogen is its low volumetric energy density compared to conventional fossil fuels, which complicates storage logistics. (Mekonnin, Wacławiak, Humayun, Zhang, & Ullah, 2025) Current methodologies typically involve high-pressure storage, which requires expensive, durable tanks, or cryogenic liquid storage, which demands energy-intensive cooling to -253°C. (Sarker, Sakib, Al-Mobin, & Resnick, 2024) While geological storage in salt caverns offers an effective solution, its application is geographically limited. Similarly, the transportation infrastructure requires massive investment; existing natural gas pipelines often require retrofitting to prevent

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embrittlement, and maritime or road transport necessitates sophisticated cooling and compression technologies. Consequently, there is an urgent need to develop more efficient, cost-effective technologies, such as chemical hydrogen carriers (LOHCs) or the conversion of hydrogen into ammonia, to facilitate easier storage and transport.

Economic Challenges:

The economic viability of the green hydrogen sector is heavily constrained by substantial initial capital expenditures (CAPEX). The construction of electrolysis plants and the simultaneous expansion of renewable energy capacity require massive upfront investment. Concurrently, the distribution network presents a financial hurdle; developing dedicated hydrogen pipelines or repurposing existing natural gas grids involves significant engineering costs, as does the deployment of a nationwide network of refueling stations for the transport sector. Beyond capital costs, operational expenditures (OPEX) remain high, as the price of green hydrogen is intrinsically linked to the fluctuating costs of renewable electricity, which is not yet universally available at competitive rates.

Green hydrogen faces stiff competition from established energy vectors. Gray hydrogen, derived from fossil fuels without carbon capture, remains significantly cheaper, while blue hydrogen offers a lower-cost, transitional low-carbon alternative. Furthermore, in the context of electrification, direct renewable energy usage (such as battery-electric vehicles) is often more energy-efficient than the conversion losses inherent in the hydrogen value chain, posing a threat to hydrogen's market share in the transport sector. To overcome these competitive disadvantages and bridge the price gap with traditional markets, the green hydrogen sector requires sustained, long-term government fiscal support and subsidies.

Political and Organizational Challenges:

The development of a global hydrogen economy is hindered by a lack of harmonized international standards and regulatory frameworks. The absence of unified agreements governing production certification and trade impedes the formation of a cohesive global market. This fragmentation is exacerbated by divergent national policies; while some nations aggressively incentivize green hydrogen, others lack the necessary regulatory structures, creating an uneven playing field that stifles cross-border investment. Additionally, logistical challenges persist regarding the coordination of international transport corridors, which are essential for connecting production centers with consumption markets.

Legislative and Regulatory Constraints:

Domestically, the growth of the hydrogen sector in Germany is often impeded by legislative frameworks originally designed for conventional energy systems. The existing laws governing energy networks are not fully adapted to the specific requirements of hydrogen, necessitating comprehensive legal updates. Furthermore, bureaucratic hurdles, such as complex and protracted licensing processes for production plants and infrastructure, slow down project implementation. Strict environmental regulations, while necessary, can further delay development. To accelerate the transition, there is a pressing need for clear incentive policies, including tax exemptions and financial mechanisms, to de-risk private sector investment and foster industrial uptake.

Investment opportunities in Green Hydrogen in Germany:

Strengthening Government Policies:

Providing Financial and Investment Incentives:

To accelerate the development of the green hydrogen sector, the German government must implement a robust framework of financial and investment incentives designed to de-risk market entry for private entities. This support can be operationalized through direct financial mechanisms, including tax exemptions

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for capital investments in hydrogen infrastructure and the provision of grants or soft loans specifically targeted at production, storage, and transport projects. Furthermore, the government plays a critical role in stimulating the private sector by injecting funds into Public-Private Partnerships (PPPs), thereby encouraging large-scale industrial commitments. Complementary to this, state-backed investment guarantees and long-term incentive programs are essential for mobilizing established corporations, while specialized support programs foster an ecosystem of startups and innovation within the clean energy landscape.

Facilitating Clean Energy Legislation:

Concurrently, the legislative environment requires significant modernization to accommodate the unique demands of the hydrogen economy. This entails updating existing laws to streamline the often complex procedures for obtaining licenses and approvals for production plants and associated infrastructure. The introduction of pro-hydrogen legislation is equally critical; this involves establishing a clear regulatory framework that supports distribution networks and mandating strict environmental standards to incentivize the industrial shift from fossil fuels to clean hydrogen. Moreover, the government must foster institutional innovation by facilitating a "triple helix" of cooperation between government bodies, research institutions, and industrial stakeholders to accelerate the adoption and deployment of hydrogen technologies.

Investment in Research and Development:

Support Innovation to Improve Production Efficiency:

Investment in research and development (R&D) constitutes a cornerstone for the economic viability of green hydrogen, particularly regarding the efficiency of electrolysis. Resources must be directed toward developing advanced electrolyzers that reduce energy consumption and maximize production rates. This includes materials science research focused on innovative components for electrochemical cells to enhance performance and lower manufacturing costs. To sustain this technological progress, Germany is prioritizing the establishment of specialized innovation hubs and technology centers, which serve to bridge the gap between academic research at universities and practical application within industrial enterprises.

Development of Low-Cost Storage and Transportation Technologies:

Parallel to production advancements, significant R&D efforts are required to optimize storage and logistics. This involves investigating alternative storage mediums, such as converting hydrogen into ammonia or utilizing solid-state storage, as well as refining high-pressure and cryogenic technologies to improve energy efficiency. Innovative transportation solutions are also being pursued, including the development of smart, safe pipeline networks and the use of Liquid Organic Hydrogen Carriers (LOHCs) to facilitate cost-effective long-distance transport. Furthermore, the integration of digitization and artificial intelligence is becoming increasingly important for monitoring infrastructure, minimizing losses, and optimizing grid management. This technological push aligns with recent government assessments; as the demand for climate-friendly hydrogen is expected to exceed initial projections, the Federal Cabinet updated the National Hydrogen Strategy in July to significantly raise future production capacity targets.

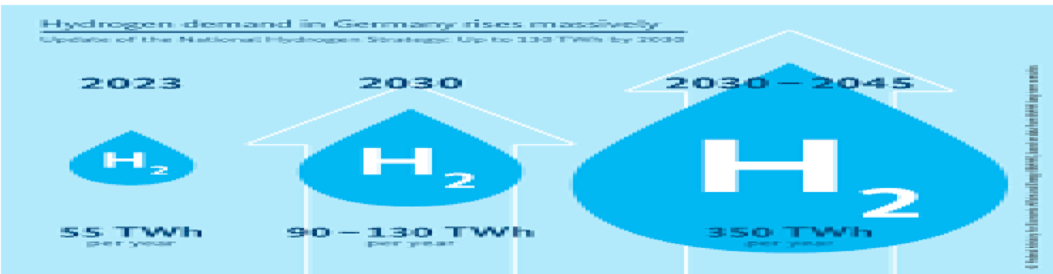

Figure04: hydrogen demand In Germany

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Strengthening International Cooperation:

Recognizing the limitations of domestic renewable generation, Germany is actively expanding strategic partnerships with countries possessing abundant solar and wind resources, particularly in Africa and the Middle East. These collaborations aim to achieve economic integration through a symbiotic relationship: Germany transfers advanced technology to partner nations in exchange for the import of competitively priced green hydrogen. A key component of this strategy is the development of international transport corridors, including offshore and onshore pipelines, to physically link production centers with European markets.

Coordination of Efforts at the European and Global Level:

Beyond bilateral agreements, Germany is leading efforts to establish a cohesive global and European hydrogen market. Within the European Union, the focus is on creating a single market through the standardization of regulations governing production, transport, and safety. On the global stage, Germany supports the formation of international alliances to regulate trade, coordinate research, and ensure fair, competitive pricing. These measures are designed to create a transparent regulatory framework that facilitates global trade flows between renewable energy producers and industrial consumers, ensuring long-term energy security.

Conclusion

Investing in green hydrogen faces significant challenges at the technical, economic and organizational levels. The high costs of its production and transportation, coupled with the need for infrastructure development, are major obstacles. The lack of international coordination and unified regulatory standards is also hindering the growth of the global hydrogen market. However, despite these challenges, it remains possible to overcome them through international cooperation, technological innovation, and continuous government support, which will enhance the role of green hydrogen in achieving a sustainable energy future.

Promoting investment in green hydrogen requires supportive government policies that provide financial and legislative incentives, along with intensive investment in research and development to improve existing technologies. International cooperation is also necessary to build strong partnerships and coordinate efforts to create a global market for green hydrogen. With these solutions, Germany can overcome the current challenges and achieve its goals of becoming a world leader in the green hydrogen sector, contributing to strengthening the economy and achieving sustainable development.

The future of green hydrogen in Germany is promising, provided that the challenges related to cost and infrastructure are overcome. By strengthening international cooperation and expanding domestic production, green hydrogen is expected to become an essential part of Germany's energy mix in the coming decades, promoting a shift towards a low-carbon economy.

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