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# Overview and Roadmap of Hydrogen Utilization in Industry

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## Abstract

Hydrogen has emerged as a promising solution for achieving a sustainable economy in various industrial sectors. This paper provides an overview of the use of hydrogen in various industrial applications, including energy and heat supply in industrial processes, raw material utilization, and transport. The benefits and role of hydrogen in industrial defossilization are discussed, highlighting its potential to reduce greenhouse gas emissions from energy-intensive industries. The storage properties of hydrogen offer a solution to decouple the availability of renewable energy from its generation time and to increase energy flexibility. In addition, the paper examines the strategic aspects of hydrogen deployment in Germany, such as policy considerations, the economic viability of hydrogen technologies, external influences such as imports, and the current technical challenges associated with its widespread adoption. Considering these aspects, an overview and a roadmap for the integration of hydrogen in industrial sectors are presented, and recommendations for a successful transition to hydrogen are given.

## Keywords

Roadmap; Hydrogen; Industry; Energy Supply; Decarbonization

## 1. Motivation

In the Paris Climate Agreement, 195 countries agreed in 2015 to reduce their climate-damaging emissions to prevent climate change and limit global temperatures [1]. To achieve this goal, 27 of the EU Member States signed the European Green Deal. Thus, the European Union aims to become carbon neutral by 2045 [2]. As an initial measure, greenhouse gas emissions should be reduced by at least 65 % until 2030 compared to 1990. In a further step, emissions should continue to fall, aiming to achieve an 88 % reduction by 2040 [3]. In Germany, greenhouse gas emissions have been continuously reduced over the past years. In 2022, they accounted for about 746 million tons of $CO_2$-equivalent (Mt $CO_2e$), which represents a reduction of 40 % compared to the 1990 levels. The main source of emission corresponded to $CO_2$ from fossil fuel combustion, which accounts for 84 % of total greenhouse gas emissions [4].

In order to achieve climate neutrality in an industrialized nation such as Germany, the reduction of $CO_2$ emissions must be continuously pushed. In 2022, the industrial sector was responsible for emitting around 164 Mt $CO_2e$. This sector is Germany's second largest source of greenhouse gas emissions after the energy supply sector, accounting for 22 % of total emissions. To achieve the 2030 targets, the industrial sector must reduce its emissions by about 70 Mt $CO_2e$ [5]. For this reason, the motivation to use hydrogen as an alternative energy source is significant. It could be used to defossilize industrial processes and generate energy or heat, as these processes often rely on fossil fuels combustion. This article provides insight into the role of hydrogen and its potential use in the industrial sector as an alternative energy carrier to reduce emissions. It also examines its future prospects.

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## 2. Industrial Hydrogen Utilization

### 2.1 Green Hydrogen as an Alternative Energy Carrier

Hydrogen, chemically $H_2$, and in Latin hydrogenium, translates "water maker". This underlines hydrogen's crucial role in water formation, which was demonstrated by the scientist Antoine Laurent de Lavoisier in 1785 [6]. Hydrogen is the most abundant element in the universe. On Earth, however, it is usually found with other elements, such as oxygen or carbon. To obtain $H_2$ in its pure form, it must be separated from the other elements. There are various methods to produce hydrogen, each labeled by a color scheme: black from coal gasification, brown from lignite gasification, grey from gas steam reforming, blue if carbon capture storage or utilization (CCS or CCU) follows the steam reforming and turquoise from methane pyrolysis. Hydrogen is only classified as green and, therefore, climate-neutral if the electricity used for the electrolysis comes from 100 % renewable sources, such as solar or wind power [7,8].

Green hydrogen can be used as an alternative energy carrier to reduce the industry's dependence on fossil fuels. It is therefore considered a key element in the energy transition and climate protection in Germany's industrial sector [9]. Green hydrogen is $CO_2$ emission-free and can be used in a wide range of industrial applications. It plays an important role in defossilizing industrial processes that cannot be electrified. In addition, hydrogen is a long-term energy storage medium to store the excess energy from renewable sources effectively. The production and storage of green hydrogen are important due to the high variability of energy production from solar and wind sources. It provides a valuable and effective solution during periods of high energy supply and low demand, as it can decouple the availability of renewable energy sources from the time of their generation due to weather conditions. The efficiency and use of renewable power plants can be fully exploited, as the plants do not need to be shut down when energy demand is low. In addition, energy flexibility is addressed to support the expansion of renewables into the industrial energy system. Hydrogen offers the advantage of excellent transportability and storability, as it can be compressed and stored in both gaseous and liquid form. It could be transported through a gas network and used as a fuel at refueling stations [10]. Finally, it allows for energy security since geopolitical developments often affect both the availability and price of fossil fuels [10,7,6].

Given the limited availability and higher costs associated with hydrogen production, it is important to prioritize direct electrification over hydrogen technologies to accelerate the defossilization process of the industrial energy system. Hydrogen should be used primarily in cases where direct electrification is not viable, such as aviation, heavy-duty transport, international shipping, and specific industrial applications. Hydrogen can also be an optimal choice, where a flexible energy system is required.

### 2.2 Current and Potential Use of Hydrogen in Industrial Applications

At present, hydrogen has significant industrial applications, particularly in the chemical industry and refineries (as shown in Figure 1). This is predominantly grey hydrogen produced by steam reforming of natural gas. However this chapter aims to explore the prospects for green hydrogen and its many potential future applications.

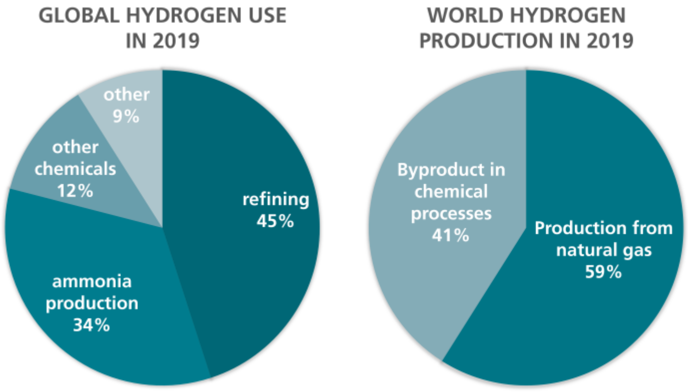

Figure 1: Global hydrogen usage by sectors in 2019, according to [11]

### 2.2.1 Hydrogen in Industrial Energy Production

Combined heat and power (CHP) plants and fuel cells provide energy-efficient conversion of hydrogen into electrical energy. For industrial applications, fuel cells can be used as decentralized power generators to produce the plant's energy requirements. By utilizing waste heat, plant efficiency can be increased while generating heat for industrial processes. Considering different manufacturers, fuel cells and CHP units offer an overall efficiency of over 80 % for the simultaneous production of heat and electricity [12–18]. The electrical efficiency of fuel cells is 1-2 % higher than that of CHP units [19–22]. The focus of fuel cells is usually on electricity generation. For CHP units, a distinction can be made between the mode of operation: heat and/or electricity-driven. The heat-driven mode is usually predominant [23]. Start-up time and dynamic operation are also important characteristics that should be considered. CHP and polymer electrolyte fuel cells (PEMFC) have a short start-up time compared to phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC). Dynamic operation and emergency power capability are only possible with CHP and PEMFC [24].

### 2.2.2 Hydrogen in Industrial Heat Production

In the industrial sector, process heat production accounts for about 67 % of final energy consumption. In addition, about 6.5 % of energy is used for heating buildings and producing hot water [25]. Industrial heat demand below 100 °C represents only 8.8 % of the total heat demand. If hot water and space heating are included, this percentage rises to 21 % [26]. Processes involving temperatures above 100 °C include the metal industry, with its melting and casting processes, and glass production, which requires high temperatures for the melting process. Paper manufacturing is also associated with cooking and drying processes. In food processing, high temperatures are used for sterilizing, cooking and drying products.

Temperatures below 100 °C can be covered by waste heat from a CHP or a low-temperature fuel cell. Fuel cells can be used in different temperature ranges. They are divided into low, medium, and high-temperature fuel cells. The electrical efficiency of a fuel cell is higher than its thermal efficiency. However, waste heat is available at different temperature levels. The polymer electrolyte fuel cell (PEMFC) and the alkaline fuel cell (AFC) are low-temperature fuel cells operating at up to 120 °C. The medium-temperature fuel cell includes the phosphoric acid fuel cell (PAFC), which operates at temperatures up to 220 °C [24].

For high-temperature applications, the molten carbonate fuel cell (MOFC) and the solid oxide fuel cell (SOFC) can operate at temperatures up to 450 °C – 1,000 °C [24]. Furthermore, the hydrogen combustion can be adapted to existing burner technology for natural gas and its associated systems. Due to hydrogen's different calorific values and combustion characteristics compared to natural gas, burner adaptation is required to maintain consistent product quality or process heat supply [6]. Several applications are currently under development, such as crucible furnaces for melting aluminum materials, which allow using pure hydrogen for combustion [27]. The most energy-intensive process in cement production is clinker production, which requires high temperatures. Hydrogen is emerging as a viable alternative, providing an opportunity to reduce emissions during the heating phase [28]. Hydrogen is also emerging as a clean-burning fuel alternative in the glass manufacturing and pulp and paper industries, offering the potential to reduce emissions in key high-temperature processes. Additionally, thermal oil systems can use hydrogen combustion to heat the thermal oil. Thermal oil is a pressureless heat transfer medium and can be used in various processes with temperatures of up to 350 °C. Another option for direct steam generation is the oxyfuel process, which is currently under development. Here pure oxygen is used for combustion to avoid the formation of $NO_x$. The combustion of pure hydrogen and pure oxygen produces water, which can be used as direct process steam after combustion [6].

### 2.2.3 Hydrogen as a Raw Material for Industrial Processes

Green hydrogen reduces $CO_2$ emissions in industrial processes where grey hydrogen is used as a raw material for the production of various materials. Here are a few examples of industrial applications:

- **In steel production,** green hydrogen can be used as a reducing agent in the Blast Furnace (BF) instead of carbon to reduce $CO_2$ emissions in the extraction of iron ore for the production of raw steel. In the BF/Basic Oxygen Furnace (BOF) process, hydrogen and combustion air reduce iron ore in the blast furnace (BF). The resulting liquid iron is then transferred to the converter (BOF) for further processing into raw steel. Initial trials have confirmed the promising direct use of hydrogen, and a second experimental phase is investigating the impact of hydrogen technology on the metallurgical processes in the blast furnace [29]. Another promising approach to steelmaking is the Direct Reduction/Electric Arc Furnace (DR/EAF) process. In this method, iron ore is reduced using hydrogen in a direct reduction (DR) plant, and the obtained iron is then introduced into the electric arc furnace (EAF). These plants are typically fuelled by natural gas, allowing the possibility of transformation to hydrogen. The direct reduction process exhibits the highest potential for emission reduction, and its application has already been successfully demonstrated in the small-scale innovation project µDRAL [6,30].
- **In the chemical industry**, hydrogen is used to produce basic chemicals such as ammonia and methanol. Ammonia, composed of nitrogen (N) and hydrogen (H), finds application in fertilizer production, as a refrigerant in cooling systems, and in the production of various chemical compounds. Methanol, produced from carbon monoxide (CO), carbon dioxide ($CO_2$), and hydrogen (H), serves as a feedstock for the synthesis of many chemical compounds, including plastics, solvents, and pharmaceuticals [31]. Currently, grey hydrogen derived from natural gas reforming is predominantly used. The chemical sector accounts for about half of the annual hydrogen demand and offers significant potential for emission reductions through substitution. As certain chemical processes rely on $CO_2$ from steam reforming, the substitution of this process with alternative carbon sources is being investigated. The Carbon2Chem project investigates the utilization of process gases, such as blast furnace gases from steel production, as carbon sources and feedstocks for basic chemicals [32].
- **In refineries,** hydrogen is used for fuel desulfurization and hydrocracking, breaking down heavy crude oil fractions to produce high-value products. Refineries are currently the most significant users of hydrogen. These processes use both grey hydrogen from natural gas reforming and on-site generated hydrogen from refinery operations [31].

### 2.2.4 Hydrogen in Industrial Transport for a Sustainable Mobility

Hydrogen in fuel cell vehicles offers an environmentally friendly solution for reducing emissions in freight transport. Whether for heavy-duty and long-haul vehicles or within logistics centers, particularly for forklift trucks, hydrogen as an energy carrier offers a sustainable alternative.

## 2.3 Key Factors for the Use of Hydrogen in Industry

Investments must be carefully balanced, considering both economic viability and sustainability. In addition, certain technologies need to reach certain development milestones (TRL levels) to become cost-effective for industrial implementation. In addition, policy choices, such as investment strategies and international cooperation, will play a key role in shaping their progress.

### 2.3.1 Political Goals for a Sustainable Transition

Europe's hydrogen strategy is ambitious: By 2050, the percentage of renewable hydrogen in the European energy mix should increase to 13-14 %. In the first phase, from 2020 to 2024, electrolyzers with a total capacity of 6 GW are planned. By 2030, the capacity is expected to reach 40 GW to promote the use of green hydrogen in the energy system. The aim is to make green hydrogen competitive with other production methods by 2030 and to support an energy system based on renewable sources. In the final phase, from 2030 to 2050, renewable hydrogen technologies should be ready for large-scale deployment across all sectors [33].

In Germany, the National Hydrogen Strategy (Nationale Wasserstoffstrategie NWS) 2020 has been adopted to accelerate the use of this climate-friendly alternative. The strategy includes establishing local production facilities, developing hydrogen technologies, expanding the hydrogen infrastructure and cooperating with international partners for imports. In this way, the market for a green hydrogen economy will be gradually prepared. By 2030 electrolyzers with 10 GW of capacity will be installed [34].

The National Hydrogen Strategy Review in July 2023, expands on the 2020 strategy with the goal of adapting the delivery of safe, sustainable, and climate-neutral hydrogen. By 2030, the new Hydrogen Strategy aims to lay the foundations for a sustainable future by ensuring an abundant supply of hydrogen, building a robust infrastructure, promoting its integration into the industrial, energy and heating sectors, and creating the optimal framework to facilitate these transitions. By 2027/2028, Germany plans to have an initial hydrogen network in place. It will consist of 1,800 km of upgraded and new hydrogen pipelines. In parallel, a "European Hydrogen Backbone" of about 4,500 km across Europe will be developed. The aim is to have a network by 2030 that directly connects all major hydrogen production, import and storage hubs with primary consumers. In 2030, hydrogen and its derivatives are expected to have widespread use in industrial applications, heavy-duty vehicles, and air and maritime shipping. In the electricity sector, hydrogen will increase energy security by means of flexible gas power plants ($H_2$-ready). Conditions for its use in centralized and decentralized heating systems are being developed. Germany aims to lead hydrogen technologies by 2030, with companies covering the entire value chain from electrolyzers to fuel cells [35].

### 2.3.2 Marketability and Economic Viability

To compete with other energy sources and achieve a breakthrough, green hydrogen’s price must be reduced further. At present, the cost of producing hydrogen is very high. Figure 2 shows the current cost of hydrogen for different production methods. Technologies for green hydrogen production need to be further developed, and the cost of fossil fuels must increase, for example, through a carbon pricing mechanism, to make green hydrogen more competitive [36]. Revenues from carbon pricing could support investment in renewable hydrogen. In 2022, the price of a $CO_2$ allowance in the EU Emissions Trading Scheme (EU-ETS) will average around €81/t$CO_2$ [37]. In 2021, the National Emission Trading Scheme (nEHS) will start selling allowances at a fixed price of €25/t$CO_2$. By 2026, the price will be set at €55-65/t$CO_2$ [38]. The National Hydrogen Strategy estimates investment expenditure for hydrogen development at least €10 billion [34]. For Europe, the investment is estimated at €180-470 billion [33].

Additionally, the development of production routes is essential. Due to continuous technological advances, the cost of electrolyzers has already fallen by 60 % compared to previous years. Improved efficiencies and economies of scale are expected to further reduce the price by 2030 [33,7]. The average capital expenses (CapEx) for electrolyzers currently are €800/kW. It is expected to fall to around €650/kW just before 2030 and to below €500/kW after 2030 [39]. The expansion of renewable energy sources will also lead to a reduction in electricity costs, which will have a positive impact on operating costs.

Figure 2 presents the projections for hydrogen production costs according to [40]. Two trends are shown for green hydrogen. Assuming a constant natural gas price and a carbon price of €100/ton, a conservative trend emerges in which green hydrogen is slightly more expensive than grey or blue hydrogen by 2050. The second trend assumes a rapid development of electrolyzers. In this scenario, green hydrogen could become cost-competitive before 2050.

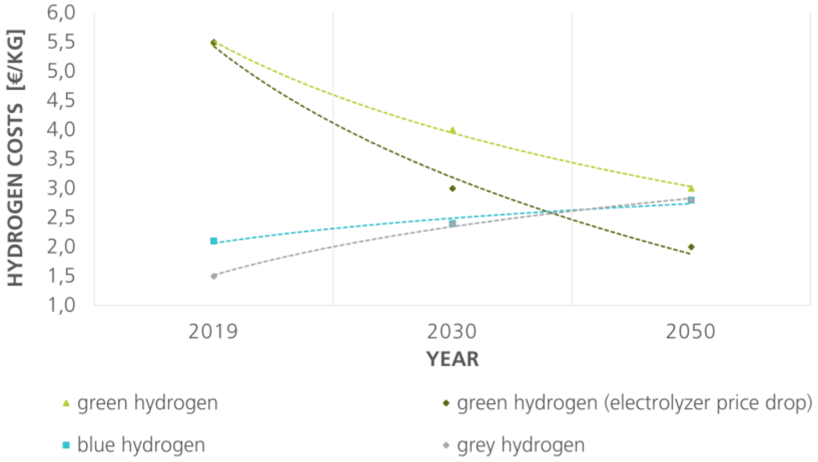

Figure 2: Hydrogen costs [€/kg] according to [40]

### 2.3.3 Technical Hurdles and Challenges of Hydrogen's Technologies

It takes about 9 kg of water to produce 1 kg of hydrogen. In addition, about 50-55 kWh of electrical energy is required. [41]. Seawater is abundant but must be desalinated before it can be used in processes such as PEM electrolyzers. New insights into hydrogen production from raw seawater by electrolysis have been successfully tested and are under development [42]. Other approaches to hydrogen production are also being explored, such as the use of biomass. In particular, the study of purple bacteria derived from fruit and dairy waste opens up promising avenues for hydrogen production [43].

Another critical issue is the availability of key materials essential for implementing a hydrogen economy. The hydrogen sector requires materials such as aluminum, copper, nickel, and zinc for developing renewable energy sources, and platinum and iridium for advancing electrolyzer technologies. However, the increasing scale of demand in the coming years may pose challenges in sourcing these materials, potentially leading to shortages or higher prices. It is projected that platinum demand for hydrogen production could exceed current production levels by more than a third by the 2030s, while iridium demand for PEM electrolyzers could increase by more than 160 % over current production levels by 2040. Given this increased demand for critical materials, the importance of recycling, improving efficiency, and extending the life of these technologies must be assessed to achieve a sustainable hydrogen economy [44].

Another technical barrier is the transport of hydrogen in the existing gas network. A hydrogen blend of up to 20 vol-% has already been achieved. Further development of up to 30 vol-% is expected [45]. Higher blends bring uncertainties about material degradation of the pipeline steel and pipeline components such as compressors, valves, or pressure-reducing stations. The handling of gas leaks is also much more delicate. Finally, end-user equipment would also need to be adapted to this blend, as the different calorific and density properties may affect the end-use application [46]. Hydrogen blending in pipelines reduces energy transmission efficiency due to its lower volumetric energy density than natural gas, requiring higher operating pressures to maintain constant transmission capacity. However, this poses challenges for steel materials. In addition, exceeding the maximum velocity can cause damage or erosion to the pipeline walls, leading to wall leaks or other problems [47].

### 2.3.4 External Influences on Hydrogen's Economy Development

Renewable energy sources, such as solar and wind, have lower operating costs than conventional fossil fuels once the equipment is amortized. Countries with abundant solar or wind resources can direct their economic growth towards renewable energy [7]. The European Hydrogen Strategy foresees partnerships with neighboring countries and regions, especially in North Africa [33].

## 2.4 Development of a Hydrogen Roadmap for Industrial Energy Supply

Based on the issues discussed in the previous chapters, a comprehensive hydrogen roadmap for the industry is proposed. This roadmap outlines the short-, medium-, and long-term goals that must be achieved to facilitate a successful transition to a hydrogen-based energy system.

The transition to renewable energy sources for industrial power supply in industry is increasing. However, renewable energy fluctuations require a flexible energy demand and storage in industries, which could be achieved through the integration of hydrogen. The results of Stuttgart University's Energy Efficiency Index survey from 2021 show that over 60 % of the companies have integrated or are integrating renewable energy within the company. In addition, more than 30 % of the companies have or plan energy storage solutions. According to the survey, the use of hydrogen in industry is currently very low at 8 %. However, about 58 % of the companies surveyed are currently investigating the use of hydrogen or have plans to investigate [48]. As renewable energy is expected to continue to grow, the industry has identified the potential of hydrogen for energy storage or as an alternative fuel and is exploring its implementation.

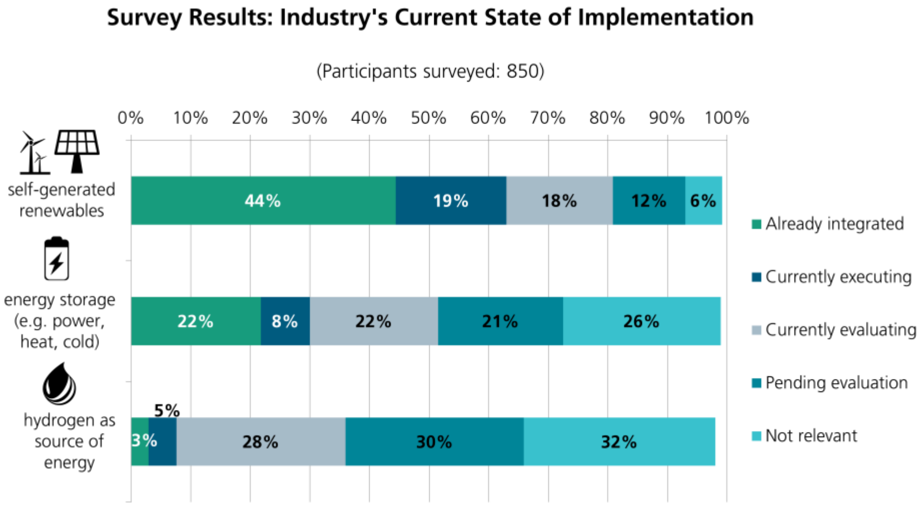

Figure 3: Survey Results: Industry's Current State of Implementation [48]

In the short and medium term, the use of $H_2$ blending in natural gas can be a solution to reduce $CO_2$ emissions for the industrial energy supply using the existing technologies. The availability of hydrogen-ready technologies allows a switch in operation without additional plant modifications. Some CHP engine manufacturers, allowing a blending percentage in the existing plant of up to 40 %, are following this approach [49]. As described in the previous chapters, it is expected that the high prices of hydrogen and electrolyzers will decrease while the import of hydrogen increase, so that in the long term hydrogen can be used economically as an energy source in industry. In addition, the development and ongoing research in hydrogen technologies will enable a long-term breakthrough in the industry.

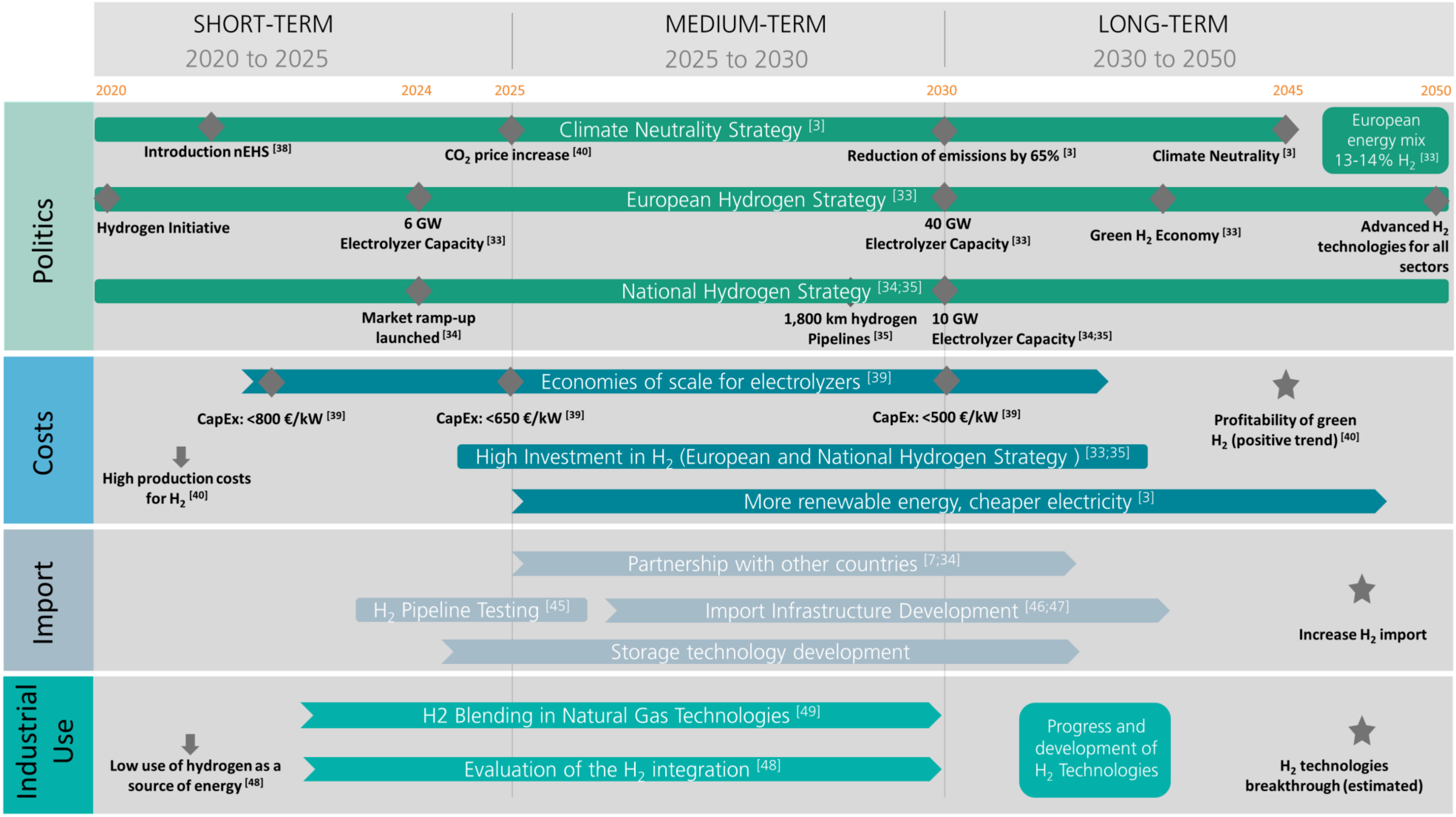

Figure 4: Hydrogen Roadmap

## 3. Summary and Outlook

This paper provides an overview of the potential development of green hydrogen technologies in industrial applications focussing on their use in achieving climate neutrality goals. The analysis considers political and economic developments as well as technical barriers associated with hydrogen production and use. The results suggest that significant hydrogen economy development can be expected after 2045. This projection is based on several factors, including expected cost reductions for hydrogen, the availability of abundant renewable energy sources, and advances in related technologies and infrastructure. Looking forward, the outlook for green hydrogen technologies appears promising. With projected cost reductions and advances in renewable energy sources, hydrogen is expected to become a viable and competitive option for various industrial applications. In addition, the continued development of technologies and infrastructure will further increase the adoption and implementation of hydrogen-based solutions. This transformation holds great potential for reducing carbon emissions and promoting sustainable industrial practices.

### 3.1.1 The Vision of an Industrial Research Platform: WAVE-H2

To achieve climate neutrality and advance the technological development of hydrogen technologies on an industrial scale, the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung BMBF) is funding the establishment of a "Versatile, Energy-Flexible, and interconnected $H_2$ Industrial Research Platform (WAVE-H2)". The University of Stuttgart will establish a dynamic hydrogen infrastructure by 2025. The aim is to investigate the optimal and flexible path for hydrogen in terms of production, distribution, storage, and consumption in industrial energy and heat supply, considering different technologies [50].

## Nomenclature

| | |
|---|---|
| CapEx | Capital Expenditures |
| CHP | Combined Heat and Power |
| FC | Fuel Cell |
| MCFC | Molten Carbonate Fuel Cell |
| PAFC | Phosphoric Acid Fuel Cell |
| PEMFC | Polymer Electrolyte Membrane Fuel Cells |
| SOFC | Solid Oxide Fuel Cell |

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