

The evolution of hydrogen technologies: paving the way to a sustainable hydrogen economy

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Nowadays, there are growing concerns about pollution, climate change and the emerging depletion of fossil fuels. The focus is on the research and development of alternative and renewable energy sources (RES). Hydrogen is emerging as a promising energy carrier to reshape the energy landscape. Fuel cell and hydrogen (FCH) technologies combine various innovations that can change the way we produce and store energy, the way we power our vehicles and mitigate the impact on the environment in general. This brief overview gives an insight into their applications, added value, potential challenges and policy initiatives, highlighting their key role for a sustainable future.

Keywords: Hydrogen, fuel cell, metal hydrides, hydrogen economy, environment

INTRODUCTION

Hydrogen has remarkable properties that make it an attractive energy carrier. Its high energy content per unit mass and zero-emission combustion properties set the stage for its various applications. The most common methods of hydrogen production include methane steam reforming, electrolysis and biomass gasification. Electrolysis, which involves splitting water molecules using electricity, is particularly notable for its potential to harness renewables such as solar and wind power, thereby making hydrogen production inherently greener. Hydrogen is usually categorized into several different colors that reflect the sources through which it is produced and processed (Fig. 1).

One of the main applications of hydrogen technology is the mobility sector. Hydrogen fuel cell vehicles (FCVs) are an environmentally friendly alternative to vehicles with internal combustion engines, as FCVs emit only water vapour as a by-product. In addition, hydrogen can also be used in the aviation and marine industries, addressing the challenges of decarbonizing these sectors with a traditionally high carbon footprint.

Another major application of hydrogen is for energy storage and grid management. RES such as solar and wind are intermittent in nature, which poses challenges to grid stability. Hydrogen can be stored and later converted into electricity *via* fuel cells during peak demand, effectively acting as a buffer to balance fluctuations in energy supply. This approach promotes the integration of renewable sources into the energy mix, making the grid more

reliable and sustainable. Nevertheless, the road to widespread hydrogen adoption is not without its challenges. Infrastructure remains a significant hurdle, as building a robust hydrogen refueling network for vehicles and integrating hydrogen storage into existing energy systems requires significant investment. In addition, the efficiency of hydrogen production methods, especially electrolysis, needs improvement to make hydrogen competitive with other energy carriers in terms of profitability [2].

The development of hydrogen technologies also raises concerns about the sustainability of production methods [3]. While electrolysis powered by renewable energy is a clean process, the current dominant method of steam methane conversion relies on fossil fuels, releasing greenhouse gases without using carbon capture and storage (CCS). In order to truly exploit the potential of hydrogen as a green energy carrier, switching to electrolysis with the use of renewable energy is imperative.

In summary, hydrogen technologies present an entirely new model for producing and storing energy and managing the entire grid system. Combined with its potential to significantly reduce greenhouse gas emissions, hydrogen is positioned as a major player in the transition to a sustainable energy future. However, it is crucial to meet the challenges of building the necessary infrastructure and reducing production costs. With continued research, innovation and collaborative efforts, hydrogen technologies have the capacity to change the energy landscape and contribute to a cleaner and greener planet.

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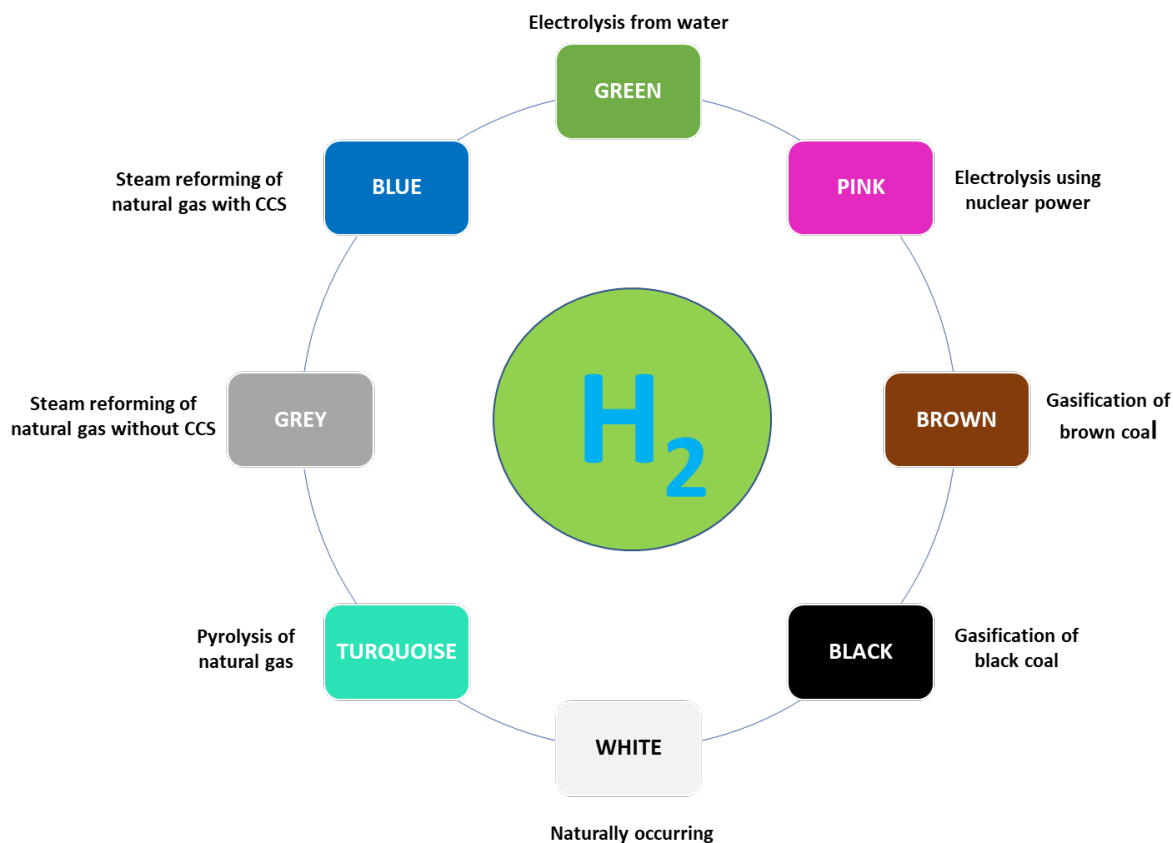


Figure 1. Colors of hydrogen by production [1]

Hydrogen Technologies and Policies across European Union Member States

The European Union (EU) has recognized the potential of hydrogen technologies to achieve its ambitious climate and energy goals, and Europe has already adopted its Hydrogen Strategy. The European Commission positions hydrogen as a core element in its clean energy policy framework. As a significant step towards this vision, the Commission unveiled a strategic proposal in July 2020 designed to accelerate the progress of green hydrogen generated from renewable sources. This strategic push aims to seamlessly integrate green hydrogen into the European energy landscape by 2050. Currently, hydrogen makes up a modest 2% of the EU's energy mix, with a significant majority, approximately 95%, derived from brown hydrogen [4, 5]. In particular, brown hydrogen is produced from natural gas or oil, resulting in annual emissions of 70-100 million tons of carbon dioxide. The paradigm shift to green hydrogen, used through electrolysis powered by renewable electricity, has the potential to revolutionize this landscape. Forecasts indicate that by 2050, ecological hydrogen could cover up to 20% of the EU's energy supply, significantly contributing to meeting the energy needs of the transport sector (20-50% of demand) and the industrial sector (5-20% of demand) [6-8].

The key elements in the European Hydrogen Strategy are as follows:

✓ *Production Methods and Green Hydrogen:* Green hydrogen, produced through electrolysis powered by renewable energy, is seen as the most environmentally friendly option. Scalability, cost-effectiveness, and availability of RES for large-scale green hydrogen production still remain as potential issues.

✓ *Infrastructure Development:* Establishing a hydrogen infrastructure for production, storage, distribution, and consumption is a significant challenge. Developing the necessary infrastructure requires substantial investment, including building new hydrogen production facilities, retrofitting existing pipelines, and/or setting up distribution networks.

✓ *Technology and Innovation:* Research, development and innovation in hydrogen technologies are crucial for improving efficiency, reducing costs, and enhancing the overall viability of hydrogen as an energy carrier. This includes advancements in electrolysis technology, fuel cells, storage solutions, and transportation methods.

✓ *Regulatory Framework:* Creating a supportive regulatory framework that addresses safety, quality, and environmental standards for hydrogen production, distribution, and usage is

essential. Harmonizing regulations across EU member states and ensuring consistency with international standards are important considerations.

✓ *Market Development and Demand:* Stimulating demand for hydrogen across various sectors, such as industry, transport, and power generation, is a key challenge. Developing incentives, subsidies, and market mechanisms to promote the adoption of hydrogen-based solutions is of essential importance.

✓ *Investment and Financing:* The successful implementation of the European Hydrogen Strategy requires substantial financial resources and is directly linked to securing public and private investments to fund research, infrastructure development, and commercial deployment of hydrogen technologies.

✓ *Global Collaboration:* Ensuring international collaboration and cooperation in the development of hydrogen technologies and markets is a priority. This involves close collaboration with third countries, sharing best practices, and creating a global hydrogen market.

✓ *Supply Chain and Raw Materials:* Hydrogen production requires raw materials, such as water and metals for electrolysis, which could raise concerns about resource availability, sustainability, and potential environmental impacts.

✓ *Skills and Workforce Development:* Building a skilled workforce to support the hydrogen sector, including engineers, technicians, and other professionals, is considered important for the successful implementation of the strategy [6, 9].

Member states have been actively pursuing various hydrogen-related initiatives, demonstrating a diverse range of applications and policy approaches [10]. In their national programs and policies, the leading EU countries focus on various aspects related to the large-scale application of hydrogen technologies:

Germany has positioned itself as a frontrunner in hydrogen technology adoption. The country's National Hydrogen Strategy, unveiled in June 2020, outlines a comprehensive roadmap for hydrogen deployment across various sectors. The strategy emphasizes both green hydrogen production through renewable-powered electrolysis and blue hydrogen through carbon capture and storage. Germany aims to have 5 GW of electrolysis capacity by 2030 and has committed significant funding to research, development, and infrastructure expansion for hydrogen technologies [11].

France is focusing on integrating hydrogen into its public transportation system. The country has launched pilot projects to test hydrogen-powered

buses and trains, with the aim of decarbonizing local transport. For instance, the "Hydrogen Mobility Ecosystem" project in the Auvergne-Rhône-Alpes region involves deploying hydrogen fuel cell buses and establishing refueling infrastructure. France's approach highlights the potential of hydrogen in reducing emissions in urban mobility [12].

The Netherlands is leveraging its expertise in offshore wind energy to produce green hydrogen. The Dutch government has set targets for installing gigawatts of offshore wind capacity by 2030, which will be used to power electrolyzers for hydrogen production. The "North Sea Wind Power Hub" initiative envisions a cooperative approach among North Sea countries to produce hydrogen from offshore wind farms and distribute it across the region [13].

Spain is focusing on the development of hydrogen industrial clusters to foster collaboration among industries, research institutions, and public entities. The country's "Hydrogen Roadmap" outlines plans to create these clusters in regions with existing industrial infrastructure. These clusters aim to integrate renewable hydrogen in industries such as steel, chemicals, and transport, contributing to sectoral decarbonization [14].

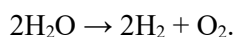
Belgium is working on cross-border hydrogen infrastructure to facilitate the transport and distribution of hydrogen within the Benelux region. The "Hydrogen for the Future" project aims to build an integrated hydrogen network connecting production, storage, and consumption facilities across Belgium, the Netherlands, and Luxembourg. This approach highlights the importance of collaboration for creating a pan-European hydrogen market [15].

In conclusion, hydrogen technologies are gaining momentum across the EU, with member states adopting diverse approaches to harness their potential. From national strategies to sector-specific projects, these initiatives demonstrate the commitment of EU countries to transition towards a cleaner and more sustainable energy future. As the technology matures and international collaboration grows, hydrogen is to play a vital role in achieving the EU's carbon neutrality goals. Furthermore, not only the EU has put efforts and funding for the development and implementation of FCH technologies. Currently, the global hydrogen market is valued at 242.7 billion USD as of 2023 and is expected to reach 410.6 billion USD by 2030. That actually presents an annual growth rate of about 7-8% during the forecast period. The growth in hydrogen demand during the recent years is due to the increasing policy measures for achieving

hydrogen-based economies and the notable investment in hydrogen infrastructure. The market for hydrogen is expected to benefit greatly from the rising use of low-emission fuel [16]. In Japan, for instance, establishing an H₂ system is identified as a key aim for Japan's future technology portfolio and the government has launched different policies in order to contribute to the realization of a low-carbon society. The share of hydrogen is expected to be 13% of the total primary energy supply in the country by 2050 under severe environmental constraints [17].

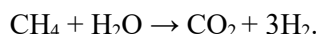
Hydrogen Production: Electrolysis and Steam Methane Reforming

Electrolytic hydrogen production involves the splitting of water molecules (H₂O) into hydrogen (H₂) and oxygen (O₂) using an electrical current. This reaction occurs at the electrode surfaces:



Electrolysis can be powered by RES, ensuring "green hydrogen" production with minimal carbon footprint.

In Steam Methane Reforming, natural gas (methane, CH₄) reacts with steam (H₂O) to produce hydrogen and carbon dioxide (CO₂):



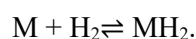
This is the most common method for industrial hydrogen production but results in CO₂ emissions unless carbon capture and storage are implemented [18].

Hydrogen Storage: Metal Hydrides and Compression. Metal Hydrides Storage Systems for RES

The conventional methods of storing and transporting hydrogen are in the form of high-pressure gas and liquid hydrogen [19]. The technically easiest way to store hydrogen is as a pressurized gas. Modern hydrogen storage containers are constructed from new composite materials that allow the weight of the container to be reduced to normal limits. However, containers take up a large volume, which is why this method is more applicable to larger vehicles such as buses and vans. Liquid hydrogen occupies a relatively small volume. Moreover, this method is characterized by the highest weight storage capacity. In order to liquefy hydrogen, however, it must be cooled to -253°C, which requires energy equal to about 1/3 of its own energy content. The tanks have expensive insulation, with a wall thickness of about 3 cm. However, a certain amount of hydrogen (about 1-3% per day) is irreversibly lost due to heating and evaporation. In

addition to being too expensive due to the high unproductive consumption of energy for compression (up to 35%) and liquefaction (up to 60%), both methods carry the risk of accidents and require serious safety measures.

The alternative of the above-mentioned methods is the storage of hydrogen in the form of metal hydrides [20]. Certain metals (e.g. Pd, Mg) and alloys (e.g. LaNi₅, FeTi) can form hydrides by absorbing hydrogen, creating a solid-state storage solution. This reversible reaction allows for hydrogen absorption and release, aiding in safe and efficient storage:



The desorption reaction is endothermic, requiring heat input [21]. When the hydride is heated, the reaction proceeds in the reverse direction. Despite the fact that a certain amount of energy is required for the release of hydrogen, in principle this ensures stability and safety - in the event of a collision, the supplied heat stops and the release of hydrogen ceases. In addition, hydrides can store about 60% more hydrogen by volume than liquid hydrogen tanks. So far, ternary metal hydrides of AB₅ and AB₂ alloys have found practical application [20]. Special units are filled with them, from which, on demand, the hydrogen is supplied to fuel cells or heating installations [22].

The advantages of the metal hydrides storage systems can be summarized as follows:

- ✓ Safe and Compact Storage: Metal hydride storage systems provide a safe and compact method of hydrogen storage compared to high-pressure gas or cryogenic liquid storage methods.
- ✓ High Energy Density: Metal hydrides can store a significant amount of hydrogen by weight, resulting in a high energy density storage solution.
- ✓ Thermal Energy Storage: The heat released during hydrogen absorption can be utilized for thermal energy storage applications, enhancing system efficiency.
- ✓ Reduced Hydrogen Loss: Metal hydrides have a relatively low rate of hydrogen loss during storage compared to other storage methods.
- ✓ Integration with RES: Metal hydrides storage systems can play a crucial role in integrating RES into the energy mix.
- ✓ Energy Storage: Excess energy generated from RES can be used to power the hydrogen desorption process, storing the energy as hydrogen in metal hydrides during periods of high renewable energy production.
- ✓ Energy Release: When renewable energy generation is low, stored hydrogen can be released

through the desorption process to generate electricity via fuel cells or combustion, contributing to a stable energy supply.

Challenges that metal hydride storage systems face are:

✓ Kinetics: The absorption and desorption reactions can be relatively slow, affecting the system's responsiveness to changes in energy demand.

✓ Heat Management: Effective heat management is crucial to ensure efficient hydrogen release.

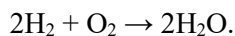
✓ Cost: Developing efficient and cost-effective metal hydride materials remains a challenge, impacting the economic viability of these systems.

In conclusion, metal hydride storage systems offer a promising way for efficiently storing and utilizing renewable energy in the form of hydrogen. With ongoing research and development efforts focused on improving reaction kinetics, material performance, and system integration, metal hydrides have the potential to contribute significantly to a more sustainable and secure energy future.

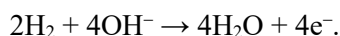
In the context of RES, metal hydrides can play a key role. For example, during periods of excess renewable energy production, the hydrogen desorption reaction can be driven by the surplus energy, storing hydrogen within the metal hydrides. When energy demand exceeds renewable energy generation, the stored hydrogen can be released through the hydrogen desorption reaction to generate electricity via fuel cells or other conversion technologies.

Hydrogen Utilization: Fuel Cells vs. Combustion

When hydrogen is burned in the presence of oxygen, it releases heat energy and forms water vapor:



The more sophisticated way for hydrogen utilization, however, is in fuel cells, which convert hydrogen and atmospheric oxygen into electricity, with water as the only byproduct. The anode reaction involves hydrogen oxidation:



Although they were discovered and demonstrated already in the first half of the 19th century, fuel cells found their first serious application only in the early 60s of the 20th century when alkaline fuel cells developed by Bacon and perfected by Pratt and Whitney, have been used in manned flights of the US space

program as sources of both electricity and water [19]. Since then, five varieties of hydrogen fuel cells - Alkaline fuel cells, Proton exchange membrane fuel cells, Fuel cells with phosphoric acid electrolyte, Carbonate melt fuel cells, and Solid oxide fuel cells, with different characteristics and possible applications have been developed [19].

Interaction with Materials: Hydrogen Embrittlement

Hydrogen can diffuse into metals, causing embrittlement and weakening of materials. This interaction is of concern in industrial applications and requires careful engineering to prevent structural failures.

Environmental Benefits and Challenges

Hydrogen offers a pathway to decarbonize sectors like transportation and industry. Hydrogen fuel cell vehicles emit only water vapor and provide longer ranges compared to battery electric vehicles. Hydrogen's versatility makes it suitable for applications like energy storage and grid balancing.

Green hydrogen production requires substantial electricity, potentially impacting grid stability. Ensuring sustainable production methods and addressing the efficiency of electrolysis are ongoing challenges. Furthermore, hydrogen's low energy density per unit volume requires advanced storage solutions for practical use.

International Collaboration and Research

Numerous research initiatives worldwide aim to enhance hydrogen production, storage, utilization efficiency, and safety. International collaboration is essential to address challenges and accelerate technological advancements.

The concept of a "hydrogen economy" envisions a transition from fossil fuels to hydrogen as a versatile energy carrier. This transformation necessitates interdisciplinary research in chemistry, materials science, engineering, and policy development.

Hydrogen technologies offer diverse opportunities to reshape energy systems while addressing environmental concerns. Scientific understanding of hydrogen's interactions, reactions, and material implications is crucial for realizing the full potential of this versatile element in building a sustainable energy future.

Integration of Hydrogen Technologies and RES

It may be pointed out that since 2010 the use of RES has notably increased as shown on Figure 2.

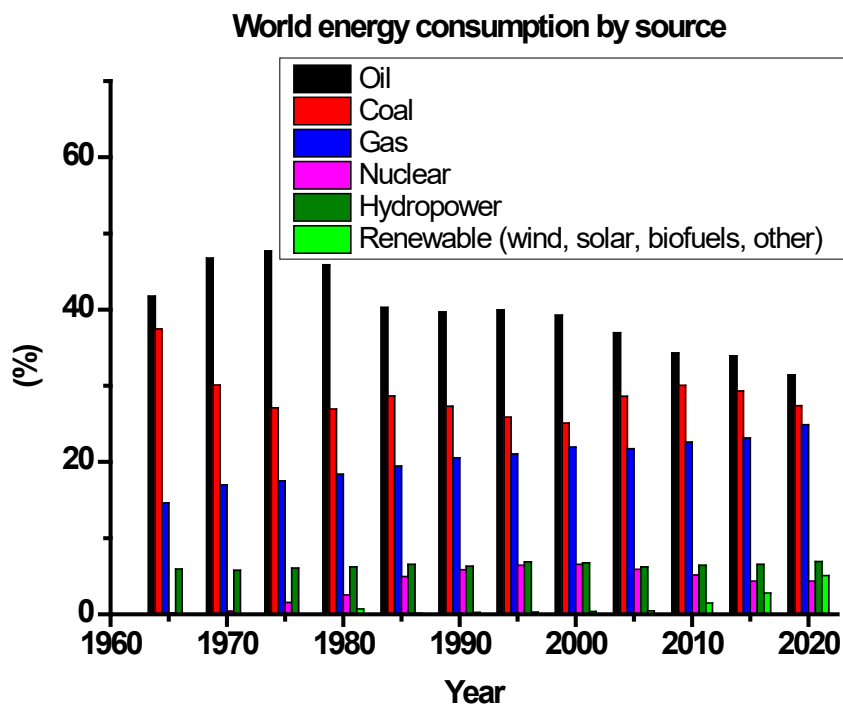


Figure 2. World energy consumption during the last six decades [23, 24]

The integration of hydrogen technologies with RES presents a powerful solution for addressing both energy demand and environmental sustainability. By harnessing the energy from renewable sources to produce, store, and utilize hydrogen, a symbiotic relationship can be established that contributes to a cleaner and more reliable energy system [25]. Here's a closer look at how hydrogen technologies and RES can be integrated [26-28]:

- ✓ Green Hydrogen Production: RES such as solar, wind, hydroelectric, and even geothermal power can be used to power electrolyzers, splitting water into hydrogen and oxygen. This process yields hydrogen without any direct carbon emissions, resulting in a clean energy carrier.

- ✓ Intermittency Management: RES are often characterized by their intermittent nature, dependent on factors like weather and time of day. Hydrogen technologies can address this intermittency by storing excess energy generated during peak production periods as hydrogen. This stored hydrogen can later be converted back into electricity through fuel cells or combustion when renewable energy generation is low, helping to balance supply and demand on the grid.

- ✓ Seasonal Energy Storage: Unlike battery storage, hydrogen has the potential to store energy for longer durations, making it suitable for seasonal energy storage. Excess renewable energy generated during the summer months, for example, can be

converted into hydrogen and stored until the winter when energy demand is higher.

- ✓ Transport and Power Generation: Hydrogen produced from RES can be used as fuel for various applications. Hydrogen fuel cell vehicles can provide zero-emission transportation, and hydrogen-powered generators can supply electricity during periods of high demand or low renewable energy availability.

- ✓ Grid Balancing and Flexibility: Hydrogen-based energy systems offer grid operators additional flexibility for managing energy supply and demand. By adjusting hydrogen production and utilization rates, grid stability can be maintained, reducing the need for fossil fuel-based backup power.

- ✓ Challenges and Considerations: While the integration of hydrogen technologies with RES holds immense promise, several challenges must be addressed:

- a) Efficiency: The efficiency of converting renewable energy into hydrogen and then back into electricity needs improvement to ensure the overall viability of the process.

- b) Cost: The cost of electrolysis, storage, and fuel cells can be prohibitive, making it necessary to drive down costs through technological advancements and economies of scale.

- c) Infrastructure: Establishing a widespread hydrogen infrastructure, including production, storage, and distribution facilities.

d) Policy and Regulation: Clear policies and regulations are needed to incentivize the adoption of hydrogen technologies and ensure a level playing field with other energy sources.

In conclusion, the integration of hydrogen technologies with renewable energy sources presents a promising trajectory toward a sustainable energy future. By harnessing the complementary strengths of hydrogen and renewable energy, an interconnected energy ecosystem can emerge, effectively curbing carbon emissions, bolstering energy security, and propelling technological advancement. However, the successful realization of this synergy hinges upon the adept handling of technical intricacies, economic considerations, and regulatory frameworks.

The prospects for hydrogen technologies on the global stage hold immense potential, coinciding with the global pursuit of cleaner and more sustainable energy paradigms. As a versatile and adaptable energy carrier, hydrogen stands poised to assume a pivotal role in driving decarbonization efforts and navigating multifaceted energy dilemmas. This prospective future is characterized by strategic investments, rigorous research endeavours, and the pervasive adoption of hydrogen across diverse sectors. Impending landscape of hydrogen technologies exemplifies a shift toward heightened sustainability within energy systems. Prioritizing the proliferation of green hydrogen production, its application in industry, transportation, energy storage, and fostering international collaboration collectively underpin its transformative capacity. Thus, hydrogen emerges as an energy carrier, holding the potential to substantially contribute to a cleaner, more robust, and ultimately carbon-neutral energy landscape.

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