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Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future

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Abstract: There is a growing interest in green hydrogen, with researchers, institutions, and countries focusing on its development, efficiency improvement, and cost reduction. This paper explores the concept of green hydrogen and its production process using renewable energy sources in several leading countries, including Australia, the European Union, India, Canada, China, Russia, the United States, South Korea, South Africa, Japan, and other nations in North Africa. These regions possess significant potential for "green" hydrogen production, supporting the transition from fossil fuels to clean energy and promoting environmental sustainability through the electrolysis process, a common method of production. The paper also examines the benefits of green hydrogen as a future alternative to fossil fuels, highlighting its superior environmental properties with zero net greenhouse gas emissions. Moreover, it explores the potential advantages of green hydrogen utilization across various industrial, commercial, and transportation sectors. The research suggests that green hydrogen can be the fuel of the future when applied correctly in suitable applications, with improvements in production and storage techniques, as well as enhanced efficiency across multiple domains. Optimization strategies can be employed to maximize efficiency, minimize costs, and reduce environmental impact in the design and operation of green hydrogen production systems. International cooperation and collaborative efforts are crucial for the development of this technology and the realization of its full benefits.

Keywords: green hydrogen production; technologies used; renewable energy; electrolysis; sustainability; efficiency improvement; leading countries in this field; net-zero gas emissions; optimization techniques

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1. Introduction

Green hydrogen, generated through the decomposition of water using renewable electricity, represents a sustainable and environmentally friendly solution. Unlike gray hydrogen produced from fossil fuels, green hydrogen production emits no carbon dioxide or other harmful pollutants. Blue hydrogen, while a step towards emissions reduction, still results in environmental emissions. Green hydrogen is being harnessed as a clean alternative across various sectors, including power generation, public transportation, and in the maritime and aviation industries. Its adoption is crucial in advancing environmental sustainability and mitigating carbon emissions, marking a significant step towards a greener future [1–4].

Green hydrogen has a wide range of applications across various sectors [5–7]. These include:

- Electricity Generation: Green hydrogen can be used as a clean fuel source in power plants, where it is converted into electricity through fuel cells.

- Transportation: Green hydrogen is suitable as a fuel for vehicles, including automobiles, buses, trains, and trucks. It can be stored in fuel tanks and converted into electricity within the vehicle using fuel cells.
- Industrial Applications: Industries that require hydrogen as a fuel or raw material, such as fertilizer, chemical, and glass manufacturing, can benefit from the use of green hydrogen.
- Aviation: Green hydrogen shows promise as a fuel for aircraft, particularly in hybrid aircraft that utilize a combination of batteries and fuel cells to convert it into electricity.

Green hydrogen represents a sustainable and environmentally friendly alternative to conventional hydrogen and fossil fuels. Its adoption is expected to contribute to environmental sustainability efforts and improve air quality. However, several challenges hinder the widespread use of green hydrogen [8–10]. These challenges include:

- Cost: The production of green hydrogen using renewable electricity is currently more expensive compared to other hydrogen production methods. This is primarily due to the costs associated with water analysis, hydrogen storage, and the establishment of renewable energy infrastructure networks.
- Infrastructure: The widespread adoption of green hydrogen requires the development of a new infrastructure for its storage, distribution, and utilization across various applications. Building this infrastructure entails significant investment.
- Efficiency: Fuel cells used for converting hydrogen into electricity are less efficient compared to alternative energy conversion mechanisms. As a result, larger amounts of hydrogen consumption are necessary to generate the same quantity of electricity.
- Safety: The utilization of green hydrogen demands stringent safety measures for storage, transportation, and usage. Specialized techniques are necessary to prevent hydrogen leakage and ensure careful handling.

Despite these challenges, it is anticipated that advancements in technology and increased investments in the field will overcome them. Several key technologies are currently being developed to enhance the utilization of green hydrogen:

- Water Analysis Techniques: New technologies with improved efficiency and lower costs are being developed for water analysis, making green hydrogen production more cost competitive.
- Hydrogen Storage Techniques: Advances are being made in the development of storage technologies that offer high efficiency and low costs, such as hydrogen storage through hydride salts.
- Fuel Cells: Ongoing advancements in fuel cell technology aim to enhance efficiency and reduce costs, making the use of green hydrogen more effective for electricity generation and vehicle operation.
- Infrastructure: Investments are being made to establish a new infrastructure for the distribution and utilization of green hydrogen, including renewable energy networks and integration with existing natural gas networks.
- Safety Control: Innovative technologies are being developed to enhance safety measures in the storage, transportation, and utilization of green hydrogen, thereby improving the overall user experience.

The advancement of these technologies necessitates substantial investments and ongoing development endeavors, with the aim of enhancing the utilization of green hydrogen by increasing its efficiency and cost effectiveness. Numerous technologies have been developed or refined to optimize the use of green hydrogen in electricity generation, among which the most noteworthy include:

- Hydrothermal Gasification: Clean coal technology utilizing hydrothermal gasification to convert coal into hydrogen gas. This hydrogen can then be used as a clean fuel, powering fuel cells to generate electricity.
- High-Temperature Fuel Cells: High-temperature fuel cells making use of the heat generated from used hydrogen fuel to produce electricity, thereby improving fuel efficiency and reducing emissions.

- Energy Storage Systems: Energy storage systems involving the use of batteries to store energy derived from the conversion of hydrogen to electricity. This stored energy can be utilized later to generate electricity as needed.
- Solid Film Fuel Cells: Ultra-clean fuel cells employing solid film technology to efficiently convert hydrogen into electricity while maintaining low emissions.
- Waste-to-Hydrogen Technologies: Waste treatment technologies can be utilized to produce green hydrogen. Organic waste can be converted into hydrogen gas through processes such as biodegradation or pyrolysis.

These technologies and processes contribute to the advancement and utilization of green hydrogen, enabling its integration into various sectors and applications.

The development and advancement of technologies related to green hydrogen utilization are of paramount importance to enhance its efficiency and cost effectiveness in electricity generation. These technologies are continuously evolving and undergoing improvements to optimize the utilization of green hydrogen. While some technologies are already deployable, such as fuel cells in vehicles, buses and trains, and battery energy storage systems widely used across various applications [11–16], others are still in the developmental phase and require further investment and refinement before commercial viability. However, numerous countries worldwide are actively engaged in developing and testing these emerging technologies through pilot projects and practical experiments. The objective is to accelerate the adoption of green hydrogen as a clean fuel source for electricity generation, transportation, and other industrial sectors.

Green hydrogen as a clean fuel offers several advantages and disadvantages. Here are some of them:

Advantages:

- Environmental Benefits: Green hydrogen is a clean fuel that does not produce harmful emissions, contributing to environmental health and improved air quality.
- Renewable and Sustainable: Green hydrogen can be produced using renewable energy sources like solar and wind energy, making it a sustainable option for meeting various energy needs.
- High Energy Conversion Efficiency: Green hydrogen is highly efficient at energy conversion. It can be used in fuel cells to generate electricity more efficiently compared to traditional fuels.
- Easy Storage and Transportation: Green hydrogen can be easily stored and transported through existing natural gas networks, making it suitable for use in industries and vehicles.

Disadvantages:

- High Production Costs: The production of green hydrogen entails high costs, including the expense of producing solar or wind energy and analyzing water to obtain hydrogen.
- Infrastructure Requirements: The use of green hydrogen necessitates the development of infrastructure for storage and transportation. This requires significant investments and ongoing development efforts.
- Safety Concerns: Green hydrogen can be dangerous if mishandled or if there is a leakage. Proper handling and adherence to safety procedures are essential.
- Technological Development: The utilization of green hydrogen relies on advanced technologies for storage, transportation, and usage. Developing these technologies and making them commercially viable requires time and effort.

It is important to consider these advantages and disadvantages when assessing the potential of green hydrogen as a clean fuel and determining its suitability for specific applications.

In broad terms, harnessing green hydrogen as a clean fuel presents numerous advantages. However, substantial efforts are required to enhance its production, storage, transportation, and utilization technologies. Additionally, the cost of production and the development of infrastructure should be considered to fully capitalize on its benefits. Nevertheless, green hydrogen is widely regarded as a sustainable and clean solution for meeting future energy demands, leading to significant focus at present on advancing the related technologies.

The different types of hydrogen are classified by color, including blue, gray, brown, black, and green, based on the technology used for hydrogen production, the energy source, and their environmental impact. Table 1 shows the differences between the different types of hydrogen [17,18]. Blue hydrogen is generated by steam reforming natural gas, which results in the production of hydrogen and carbon dioxide. The captured CO_2 is stored underground, but some may still escape, and the long-term effects of storage are uncertain [19,20]. Gray hydrogen is produced in a similar process to blue hydrogen, but the CO_2 is not captured, and is instead released into the atmosphere [21]. Brown hydrogen is the most commonly used type of hydrogen, produced from hydrocarbon-rich feedstock via gasification, but it releases significant amounts of CO_2 into the atmosphere. Black hydrogen is generated by coal gasification, and the hydrogen is separated from the other gases using special membranes or absorbers, while the remaining gases are released into the atmosphere [22,23]. In contrast, green hydrogen is produced using renewable water and electricity through the process of electrolysis, which splits water into hydrogen and oxygen using electricity and produces zero carbon emissions [24].

Table 1. Hydrogen color shades and their technology, cost, and CO_2 emissions.

Hydrogen Color	Production Technology	Cost	CO_2 Emissions
Blue	Steam reforming of natural gas, with carbon capture and storage	Moderate	9–12 kg CO_2/kg H_2
Gray	Steam reforming of natural gas, without carbon capture and storage	Low	16–18 kg CO_2/kg H_2
Brown	Gasification of coal or other hydrocarbon-rich feedstock	Moderate	19–25 kg CO_2/kg H_2
Black	Coal gasification, with hydrogen separation and other gases released into the atmosphere	High	24–28 kg CO_2/kg H_2
Green	Electrolysis of water using renewable energy sources	High	Zero CO_2 emissions

Note that the cost and CO_2 emissions figures given above are provided as examples only and may vary depending on a range of factors, including the specific technology used, the cost of energy and feedstock, and the efficiency of the production process.

This paper aims to explore the significant role of green hydrogen in the transition towards a sustainable and low-carbon energy landscape. It addresses the pressing need to integrate renewable energy sources with the production and utilization of green hydrogen, highlighting its potential to drive the energy sector's transformation.

The main objectives of this paper are as follows:

1. Highlighting the Importance of Green Hydrogen: The manuscript aims to emphasize the significance of green hydrogen as a key solution in achieving a sustainable energy future. It will shed light on its unique characteristics, including its ability to be produced through renewable energy sources and its potential to decarbonize various sectors.
2. Examining the Integration of Renewable Energy Sources: The manuscript will delve into the integration of renewable energy sources, such as solar and wind power, in the production of green hydrogen. It will explore the technological advancements, challenges, and opportunities associated with this integration process.
3. Assessing the Environmental and Economic Benefits: The manuscript will evaluate the environmental benefits of green hydrogen, including its contribution to reducing greenhouse gas emissions and mitigating climate change. Furthermore, it will analyze

the economic opportunities and market potential associated with the widespread adoption of green hydrogen technologies.

4. Exploring Applications and Sectoral Integration: The manuscript will explore the diverse range of applications for green hydrogen across various sectors, such as transportation, industry, and power generation. It will examine how green hydrogen can be effectively integrated into existing energy systems, fostering a sustainable and resilient energy future.
5. Identifying Policy, Regulatory, and Technological Implications: The manuscript will discuss the policy frameworks, regulatory mechanisms, and technological advancements required to facilitate the widespread adoption of green hydrogen. It will address the challenges and opportunities associated with scaling up production, storage, and distribution infrastructure.

By addressing these objectives, this paper aims to provide a comprehensive overview of the potential of green hydrogen in integrating renewable and sustainable energy sources into the energy future. It seeks to contribute to the existing knowledge base and facilitate informed discussions among policymakers, researchers, and industry stakeholders to accelerate the global transition towards a greener and more sustainable energy landscape.

This paper is structured into seven sections to provide a comprehensive understanding of green hydrogen. The first section offers an overview of green hydrogen, laying the foundation for subsequent discussions. The second section focuses on the techniques, performances, and optimization approaches related to water electrolysis, which play a crucial role in designing and operating green hydrogen production systems. In the third section, the outcomes of water electrolysis are examined, shedding light on its practical applications. Moving on, the fourth section presents a literature review highlighting the leading countries in the field of green hydrogen, emphasizing projects, benefits, and technologies reliant on renewable energy sources. In section five, innovative methods for producing and utilizing green hydrogen are explored, showcasing promising advancements. Section six delves into the challenges, recommendations, and expectations surrounding the demand for green hydrogen. Finally, the paper concludes by summarizing key insights and outlining future research directions, underscoring the need for further investigation in this evolving field.

2. Green Hydrogen Energy Policy Review Methodology

2.1. Methodology

The methodology for reviewing green hydrogen energy policies typically involves several steps. While the specific approach may vary depending on the context and objectives of the review, here is a general outline of the methodology [25]. Figure 1 gives a visual representation of the adopted methodology.

Step 1. Define the scope and objectives: Clearly define the scope of the policy review, including the geographical focus, policy timeframe, and specific objectives. Determine the key questions or areas of interest that the review aims to address.

Step 2. Literature review: Conduct a comprehensive review of existing literature, research papers, reports, and relevant policy documents related to green hydrogen energy policies. This helps to gather information on the current state of policies, best practices, challenges, and opportunities.

Step 3. Stakeholder interviews and consultations: Engage with relevant stakeholders involved in green hydrogen energy, such as government agencies, industry associations, research institutions, and non-governmental organizations. Conduct interviews, focus group discussions, or surveys to gather insights, perspectives, and feedback on existing policies and their effectiveness.

Step 4. Policy analysis: Analyze the existing green hydrogen energy policies, including regulatory frameworks, incentives, funding mechanisms, and targets. Evaluate the strengths, weaknesses, gaps, and barriers associated with the policies. Assess their alignment with national or regional energy goals, climate targets, and sustainability objectives.

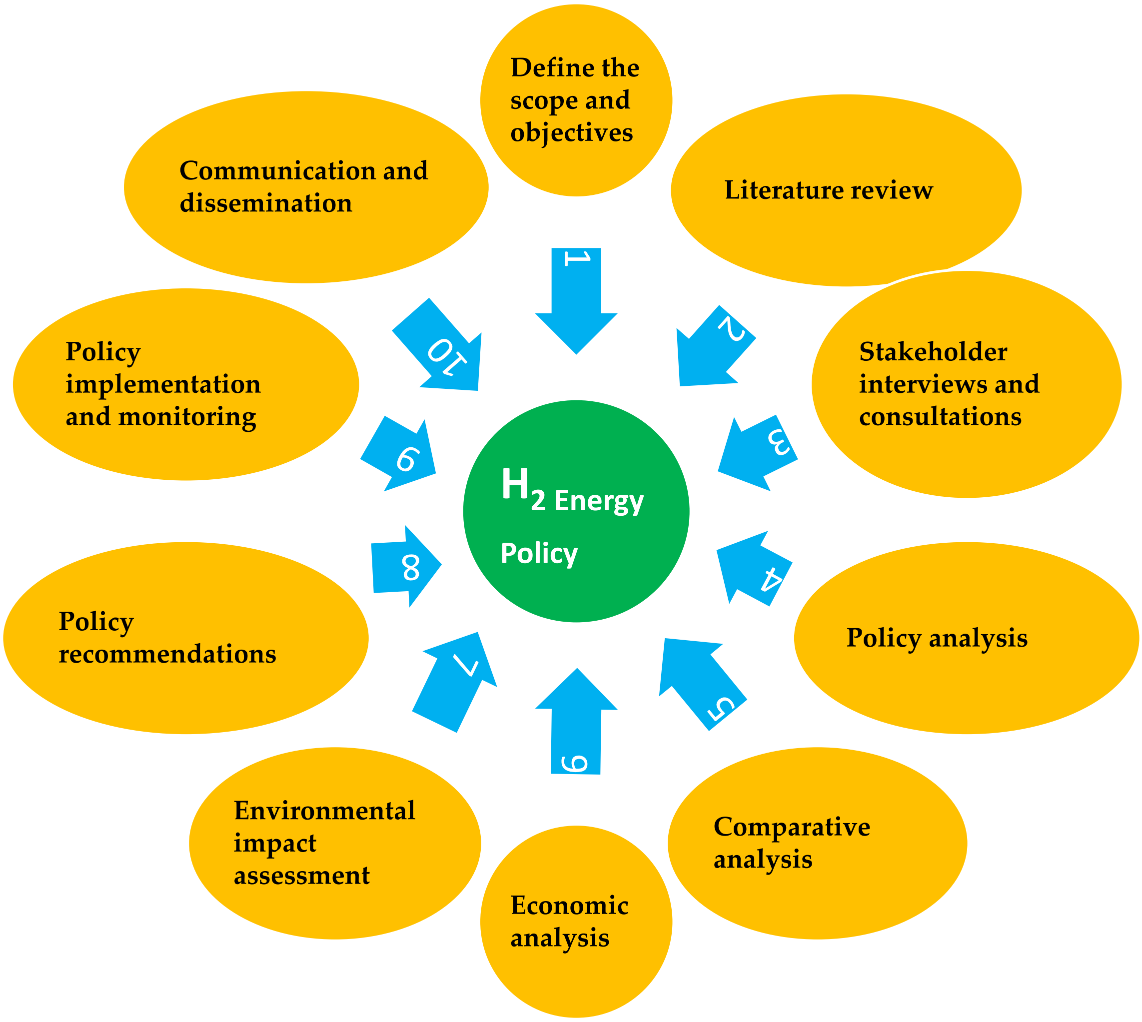

Figure 1. Green hydrogen energy policy review methodology.

Step 5. Comparative analysis: Compare the reviewed policies with international or regional benchmarks and best practices. Identify successful case studies and lessons learned from other jurisdictions that can inform policy improvements.

Step 6. Economic analysis: Assess the economic viability and cost effectiveness of green hydrogen energy policies. Evaluate the financial incentives, subsidies, and support mechanisms provided to promote green hydrogen production, infrastructure development, and market uptake. Analyze the potential economic impacts, job creation potential, and long-term sustainability of the policies.

Step 7. Environmental impact assessment: Evaluate the environmental implications and carbon footprint associated with green hydrogen production and utilization. Assess the policies' contributions to reducing greenhouse gas emissions, air pollution, and other environmental benefits. Consider the life cycle analysis of green hydrogen technologies and their integration into the broader energy system.

Step 8. Policy recommendations: Based on the findings and analysis, develop policy recommendations for improving or formulating effective green hydrogen energy policies. These recommendations should address identified gaps, barriers, and challenges. Consider the socioeconomic, environmental, and technological aspects to ensure a holistic approach.

Step 9. Policy implementation and monitoring: Provide guidance on the implementation and monitoring of the recommended policies. Outline strategies for stakeholder engagement, capacity building, and regular policy evaluation to track progress and make necessary adjustments over time.

Step 10. Communication and dissemination: Prepare a comprehensive report summarizing the policy review methodology, findings, and recommendations. Communicate the results to relevant stakeholders, policymakers, and the public to raise awareness and support for green hydrogen energy policies.

It is important to note that the methodology may vary based on the specific context and requirements of the policy review. The outlined steps provide a general framework for conducting a comprehensive and evidence-based analysis of green hydrogen energy policies.

2.2. Methods of Hydrogen Production

Historically, the majority of commercial hydrogen production has been derived from fossil fuels, primarily natural gas, oil, and coal, as shown in Figure 2. These processes are known as steam methane reforming (SMR), partial oxidation, and coal gasification, respectively. These methods are collectively referred to as "gray hydrogen" or "brown hydrogen", because they release carbon dioxide (CO_2) emissions during the production process [26].

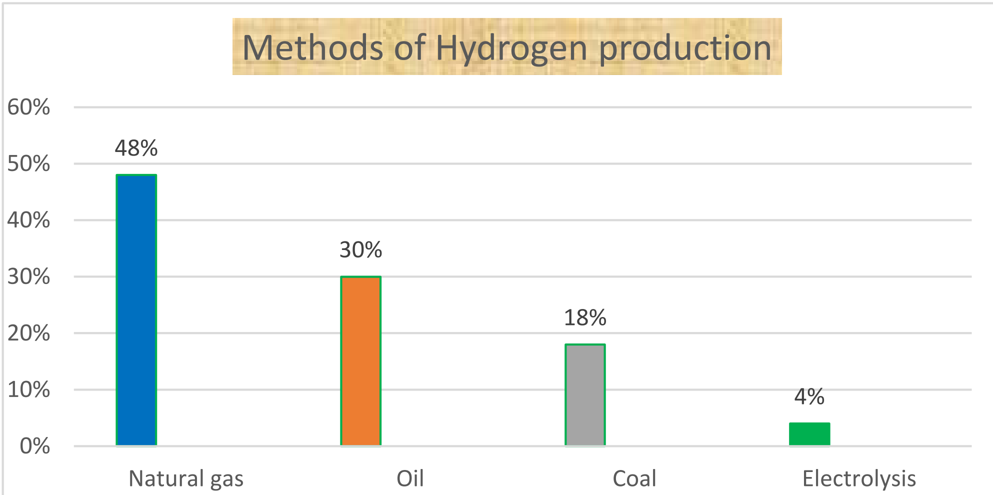

Figure 2. Methods of hydrogen production.

Natural gas is the most common feedstock for hydrogen production, accounting for approximately 48% of the world's hydrogen production. Steam methane reforming involves reacting natural gas with steam to produce hydrogen and carbon monoxide. The resulting mixture, called synthesis gas or syngas, is then further processed to separate hydrogen.

Oil, including crude oil and petroleum products, is another source of hydrogen, contributing around 30% of global production. Hydrogen can be obtained as a byproduct of various oil refining processes, such as catalytic reforming or hydrocracking.

Coal, though less common than natural gas and oil, still accounts for approximately 18% of the world's hydrogen production. Coal gasification is the process of converting coal into syngas, which can be further processed to produce hydrogen.

Electrolysis, the process of splitting water molecules into hydrogen and oxygen using electricity, accounts for about 4% of global hydrogen production. This method is known as "green hydrogen", because it can be powered by renewable energy sources, such as solar or wind power, resulting in zero direct carbon emissions.

However, it is important to note that these percentages may vary depending on the specific time period and regional factors. In recent years, there has been a growing interest in increasing the share of electrolysis-based green hydrogen production due to its potential for carbon neutrality and sustainability; that is the subject of the following section.

3. Results of Water Electrolysis

3.1. Chemical Equation

The electrolysis of water is represented by the following chemical equation [27]:

$$2H_2O(l) \rightarrow 2H2(g) + O_2(g) \quad (1)$$

This equation illustrates that two water molecules (H_2O) are converted into two hydrogen molecules (H_2) and one oxygen molecule (O_2) during the electrolysis process. Electrolysis involves the use of an external electrical energy source, typically a direct-current (DC) power supply, to drive the oxidation of water at the anode and the reduction of water at the cathode.

The electrolysis process can be further described by the following half-reactions:

$$\text{Anode: } 2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^- \quad (2)$$

$$\text{Cathode: } 4H_2O(l) + 4e^- \rightarrow 2H_2(g) + 4OH^-(aq) \quad (3)$$

By combining these half-reactions and canceling out the electrons, the overall reaction is obtained as follows:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \quad (4)$$

The minimum energy required for this reaction can be calculated using the following equation:

$$E = \Delta G/Nf \quad (5)$$

where E is the applied voltage, ΔG is the Gibbs free energy change, n is the number of electrons transferred (four electrons in this case), and F is the Faraday constant. The Gibbs free energy change (ΔG) for the reaction is given by:

$$\Delta G = -nFE^\circ \quad (6)$$

The standard electrode potentials (E°) for the respective half-reactions are:

$$E^\circ(H_2O \rightarrow 1/2O_2 + 2H^+) = +1.23 \text{ V} \quad (7)$$

$$E^\circ(2H_2O + 2e^- \rightarrow H_2 + 2OH^-) = -0.83 \text{ V} \quad (8)$$

Therefore, the overall standard electrode potential (E°) for the reaction is:

$$E^\circ = E^\circ(H_2O \rightarrow 1/2O_2 + 2H^+) - E^\circ(2H_2O + 2e^- \rightarrow H_2 + 2OH^-) = +2.06 \text{ V} \quad (9)$$

Practically speaking, there are various techniques for performing the electrolysis of water, such as alkaline electrolysis, polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolysis. These techniques differ in their operating conditions, efficiency, and cost, and are utilized in different applications based on specific process requirements. For instance, PEM electrolysis is commonly used for small-scale applications, while alkaline electrolysis is more prevalent in larger-scale industrial processes [28].

Figure 3 illustrates the electrolysis of water as the primary method for producing green hydrogen utilizing renewable electricity from solar (ws) and wind (we) sources. This process involves the passage of an electric current through an aqueous solution containing hydrogen ions (H^+) and hydroxyl ions (OH^-). The electrolysis process results in the generation of hydrogen gas (H_2) at the negative electrode and oxygen gas (O_2) at the positive electrode.

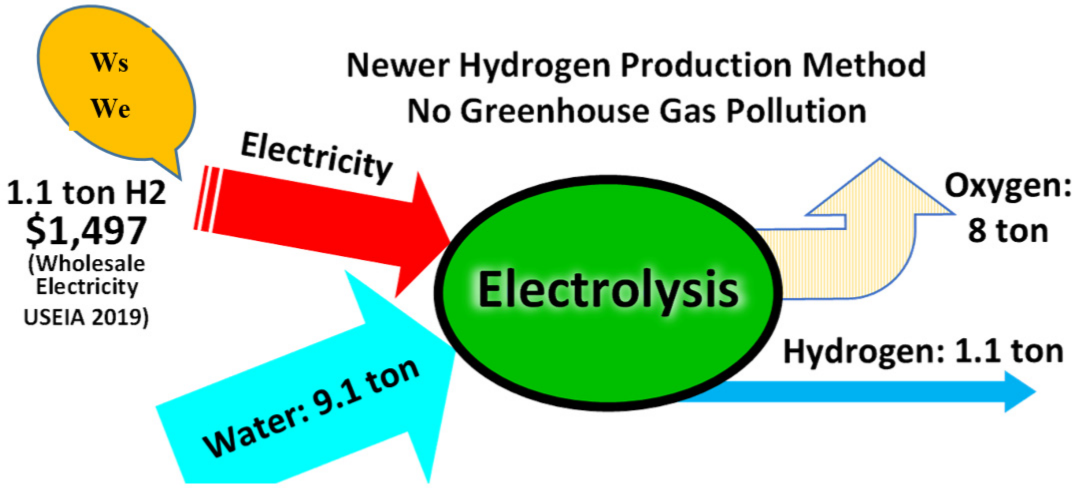

Figure 3. Inputs and outputs of water electrolysis to produce hydrogen and the absence of greenhouse gases [29].

The inputs to this process include water containing hydrogen and hydroxyl ions, as well as renewable electricity obtained from solar and wind sources. The renewable electricity is utilized to decompose the water molecules into their constituent elements, hydrogen and oxygen.

The outputs of the electrolysis process are green hydrogen (H_2) and oxygen (O_2). The produced hydrogen is captured and stored in specialized tanks for later use as an energy carrier. The oxygen, on the other hand, is safely released into the atmosphere without causing any harm or adverse environmental effects.

The production of green hydrogen through this process is advantageous, as it does not involve the emission of harmful gases or greenhouse gases. It is considered an environmentally friendly and sustainable option for energy production, contributing to the reduction of carbon emissions and mitigating climate change.

Therefore, the electrolysis of water using renewable electricity enables the production of green hydrogen, offering a clean and sustainable alternative for various energy applications.

3.2. Electrolysis Techniques

Differences between alkaline, PEM, and solid oxide electrolysis can be explained as follows [28]:

1. Alkaline Electrolysis: Alkaline electrolysis is a well-established and widely used method for producing hydrogen through water electrolysis. In this method, a solution of potassium or sodium hydroxide serves as the electrolyte, and the electrodes are typically made of nickel or nickel-plated materials. Alkaline electrolysis operates at relatively high temperatures (60–90 °C) and pressures (1–30 bar). It is commonly employed in large-scale industrial applications due to its relatively low cost and high efficiency. However, the corrosive nature of the electrolyte can lead to electrode degradation over time, limiting its use.
2. Polymer Electrolyte Membrane (PEM) Electrolysis: PEM electrolysis is a more advanced method of hydrogen production through water electrolysis. It utilizes a solid polymer electrolyte membrane to separate the anode and cathode compartments, and platinum-based catalysts are employed on both sides of the membrane to facilitate the electrochemical reactions. PEM electrolysis operates at lower temperatures (30–80 °C) and pressures (1–10 bar) compared to alkaline electrolysis. It offers higher efficiency and faster response times. PEM electrolysis is particularly suitable for small-scale applications like fuel cell vehicles or portable power systems due to its compact size and low maintenance requirements.

3. Solid Oxide Electrolysis: Solid oxide electrolysis is a relatively new and still-developing method for hydrogen production through water electrolysis. It employs a solid oxide electrolyte to separate the anode and cathode compartments, with a high-temperature ceramic material serving as the electrode. Solid oxide electrolysis operates at high temperatures (600–1000 °C), enabling higher efficiency and faster reaction rates. However, maintaining the high temperature requires significant energy input. Solid oxide electrolysis is still in the experimental stage, but holds potential for offering high efficiency and scalability for large-scale industrial applications.

The choice of electrolysis method depends on the specific application requirements, including scale, efficiency, cost, and operating conditions. Alkaline electrolysis is well suited for large-scale industrial applications, while PEM electrolysis is more suitable for small-scale applications that prioritize high efficiency and fast response times. Solid oxide electrolysis is still being developed, but shows promise for large-scale industrial applications in which high efficiency and scalability are crucial.

3.3. Electrolysis Performance Calculation

Various calculations are utilized in the context of green hydrogen production [30]. These calculations serve important roles in optimizing efficiency, reducing costs, and minimizing environmental impacts. Here are some examples:

1. Electrolysis Efficiency Calculation: One crucial calculation is determining the efficiency of the electrolysis, which measures the ratio of the energy required to produce a specific quantity of hydrogen to the energy contained within that hydrogen. The efficiency of electrolysis can be computed using the following equation:

$$\text{Efficiency} = (2 \times \text{Faraday constant} \times \text{cell voltage})/\text{Lower Heating Value of Hydrogen} \quad (10)$$

This equation takes into account the electrical energy needed for hydrogen production and the energy content of the produced hydrogen. For instance, if electrolysis requires 50 kWh of electrical energy to generate 1 kg of hydrogen, and the lower heating value of hydrogen is 39.4 kWh/kg, then the efficiency of electrolysis can be calculated as:

$$\text{Efficiency} = (2 \times 96{,}485 \times 1.23)/39.4 = 76.5\% \quad (11)$$

This calculation aids in optimizing electrolysis design and operation to enhance efficiency and minimize costs.

2. Renewable Energy Integration Optimization: Another important aspect is the integration of renewable energy sources, such as solar or wind power, into the green hydrogen production process. Optimization techniques are employed to determine the optimal size and location of renewable energy sources, as well as the optimal operation of the electrolysis and hydrogen storage systems. The goal is to maximize the utilization of renewable energy and minimize costs. For instance, studies conducted by the National Renewable Energy Laboratory (NREL) have shown that the ideal combination of solar and wind power for green hydrogen production varies depending on the location and specific requirements of the hydrogen production process.
3. Life Cycle Assessment (LCA): Life cycle assessment involves a comprehensive analysis of the environmental impacts associated with a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal. LCAs are employed to optimize the design and operation of green hydrogen production systems, aiming to minimize environmental impacts and enhance sustainability. For instance, an LCA study conducted by the International Energy Agency (IEA) revealed that the environmental impacts of green hydrogen production depend on various factors, including the electricity source used for electrolysis, the type and source of water employed, and the transportation and storage methods used for hydrogen.

Thus, performance calculations play a significant role in the design and operation of green hydrogen production systems. These calculations enable the maximization of efficiency, cost reduction, and minimization of environmental impacts.

3.4. Green Hydrogen Optimization Techniques

There are several optimization techniques used in the design and operation of green hydrogen production systems to maximize efficiency, minimize costs, and minimize environmental impacts. Here are a few examples:

- Techno-Economic Analysis (TEA): Techno-economic analysis (TEA) is a method used to evaluate the economic feasibility of a technology or process, taking into account both technical and economic factors. TEA can be used to optimize the design and operation of green hydrogen production systems, to minimize costs and maximize profitability. For example, TEA can be used to evaluate different electrolysis technologies, renewable energy sources, and hydrogen storage options, and to determine the optimal size and configuration of the production system [31,32].
- Life Cycle Assessment (LCA): Life cycle assessment (LCA) is a method used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal. LCA can be used to optimize the design and operation of green hydrogen production systems, to minimize environmental impacts and maximize sustainability. For example, LCA can be used to evaluate the greenhouse gas emissions, water use, and other environmental impacts of different electrolysis technologies, renewable energy sources, and hydrogen storage options [33,34].
- Supply chain optimization: Supply chain optimization is a method used to optimize the production and distribution of a product, taking into account factors such as cost, efficiency, and environmental impacts. Supply chain optimization can be used to optimize the design and operation of green hydrogen production systems, to minimize costs and minimize environmental impacts. For example, supply chain optimization can be used to determine the optimal location of the production facility, the optimal transportation routes and modes, and the optimal distribution network [35,36].
- Control system optimization: Control system optimization is a method used to optimize the control and operation of a process or system, taking into account factors such as efficiency, safety, and reliability. Control system optimization can be used to optimize the design and operation of green hydrogen production systems, to maximize efficiency and minimize costs. For example, control system optimization can be used to optimize the operation of the electrolysis and hydrogen storage system, to minimize energy consumption and maximize hydrogen production [37].

Hence, these optimization techniques can be used in combination to optimize the design and operation of green hydrogen production systems, to maximize efficiency, minimize costs, and minimize environmental impacts.

3.5. Green Hydrogen Production Estimation until 2050

Estimating the production of green hydrogen in the leading countries in the world from 2020 until 2050 is a complex task, as it depends on a variety of factors such as policy support, technological development, market demand, and the availability of renewable energy sources. However, some estimates and projections have been made by various organizations and research institutions [38].

- Europe: The European Union has set a target of producing 40 GW of green hydrogen by 2030, and 10 million tonnes of renewable hydrogen by 2030. According to a report by the Hydrogen Council, Europe could produce up to 800 TWh of hydrogen per year by 2050, with a potential market size of up to EUR 630 billion per year.
- China: China has set a target of producing 5 million tonnes of hydrogen per year by 2025, with a focus on green hydrogen produced from renewable energy sources. According to a report by the International Energy Agency (IEA), China could produce

up to 60 million tonnes of hydrogen per year by 2050, with a potential market size of up to USD 150 billion per year.

- United States: The United States has set a target of producing 5 GW of hydrogen by 2030, with a focus on green hydrogen produced from renewable energy sources. According to a report by the Hydrogen Council, the United States could produce up to 25% of the world's hydrogen demand by 2050, with a potential market size of up to USD 140 billion per year.
- Japan: Japan has set a target of producing 300,000 tonnes of hydrogen per year by 2030, with a focus on green hydrogen produced from renewable energy sources. According to a report by the Hydrogen Council, Japan could produce up to 20% of the world's hydrogen demand by 2050, with a potential market size of up to USD 80 billion per year.
- Australia: Australia has set a target of producing hydrogen at a cost of less than AUD 2 per kilogram by 2030, with a focus on green hydrogen produced from renewable energy sources. According to a report by the Australian Renewable Energy Agency (ARENA), Australia could produce up to 10% of the world's hydrogen demand by 2050, with a potential market size of up to AUD11 billion per year.

Thus, these estimates and projections suggest that the production of green hydrogen is expected to grow significantly in the leading countries in the world from 2020 to 2050, driven by policy support, technological development, market demand, and the availability of renewable energy sources.

4. Leading Countries in This Field

4.1. Summary of the Current Production and Utilization of Green Hydrogen

A summary of the current production and utilization of green hydrogen in the leading countries in this field [39–42].

4.1.1. Countries

1. Germany: Germany aims to become a global leader in hydrogen technologies. It has set a target of producing 5 gigawatts (GW) of electrolytic hydrogen by 2030 and 10 GW by 2040. The country is investing in research, infrastructure, and projects to support the production and utilization of green hydrogen across various sectors.
2. Australia: Australia has significant potential for green hydrogen production due to its abundant renewable energy resources. The country aims to become a major exporter of green hydrogen and has several projects underway. The Australian government has set a target of producing hydrogen at less than AUD 2 per kilogram by 2030, making it cost-competitive with other energy sources.
3. Japan: Japan is a major consumer of hydrogen and has ambitious goals for hydrogen utilization. The country aims to have 800,000 fuel cell vehicles and 5.3 million residential fuel cells in operation by 2030. Japan is also investing in hydrogen infrastructure, including hydrogen refueling stations and hydrogen-powered trains.
4. Netherlands: The Netherlands has set a target to have 500 megawatts (MW) of electrolyze capacity by 2025 and 3–4 GW by 2030. The country is focusing on developing hydrogen clusters, integrating hydrogen into industrial processes, and establishing hydrogen infrastructure for transport and energy storage.
5. United States: The United States is actively promoting the production and utilization of green hydrogen. The Department of Energy has launched the Hydrogen Shot initiative, aiming to reduce the cost of clean hydrogen by 80% to USD 1 per kilogram by 2030. The country has several projects and pilot plants for green hydrogen production, particularly in regions with abundant renewable energy resources like California and the Gulf Coast.
6. Chile: Chile has vast renewable energy potential, particularly in solar and wind power. The country aims to become a leading exporter of green hydrogen. It plans to install 5 GW of electrolyze capacity by 2025, and aims to produce the cheapest green

hydrogen in the world. Chile is also developing hydrogen-production facilities and exploring export opportunities to countries like Japan, South Korea, and Europe.

7. Saudi Arabia: Saudi Arabia, known for its abundant solar resources, is investing in green hydrogen production. The country aims to become a major global player in the green hydrogen market and has plans to develop projects totaling over 4 GW of electrolyze capacity. Saudi Arabia intends to leverage its existing infrastructure and expertise in the energy sector to produce, store, and export green hydrogen.
8. South Korea: South Korea has a strong focus on green hydrogen as part of its energy transition strategy. The country aims to produce 5.26 million tons of hydrogen per year by 2040, with a significant portion coming from renewable sources. South Korea is also promoting the use of hydrogen in transportation, industry, and power generation, and is investing in research and development to advance hydrogen technologies.
9. India:
    - Green Hydrogen Production: India has been focusing on renewable energy deployment and has set a target of 450 GW of renewable energy capacity by 2030. This commitment to renewables provides a strong foundation for green hydrogen production. The government has launched the National Hydrogen Mission, aiming to scale up hydrogen production and promote its use in various sectors.
    - Transportation Sector: India is exploring the use of green hydrogen in transportation. The government has plans to develop hydrogen fueling infrastructure and promote the adoption of hydrogen-powered vehicles. Initiatives include the development of hydrogen-powered buses, cars, and two-wheelers, as well as the establishment of hydrogen refueling stations.
    - Industrial Applications: Industries in India, such as steel, cement, and chemicals, are exploring the utilization of green hydrogen to decarbonize their operations. Green hydrogen can be used as a reducing agent or heat source, replacing fossil fuels in industrial processes. This transition can significantly reduce greenhouse gas emissions in these sectors.
10. Canada:
    - Abundant Renewable Resources: Canada possesses vast renewable energy resources, including hydro, wind, and solar power. These resources can be harnessed to produce green hydrogen through electrolysis. Several projects are underway to develop large-scale electrolysis facilities powered by renewable energy, enabling the production of green hydrogen.
    - Export Potential: Canada aims to leverage its green hydrogen production capacity for domestic use as well as for export. The country has the advantage of being well positioned to supply green hydrogen to international markets, including the United States and Europe. The export of green hydrogen can contribute to Canada's economic growth and support global decarbonization efforts.
    - Industry Transition: The Canadian government is working with industries such as steel, mining, and oil sands to explore the integration of green hydrogen in their operations. This includes using green hydrogen as a reducing agent in steelmaking, replacing carbon-intensive processes. The adoption of green hydrogen in these industries can help reduce their carbon footprint and support the country's climate goals.
11. China:
    - Hydrogen Economy Plans: China has set ambitious targets to become a global leader in the hydrogen economy. The country aims to expand its hydrogen production capacity, with a focus on both blue and green hydrogen. China has plans to develop large-scale hydrogen production projects, including coal gasification with carbon capture and storage (CCS), as well as renewable-energy-powered electrolysis facilities.

- Transportation and Mobility: China is exploring the use of hydrogen fuel cells and hydrogen combustion technologies in transportation. The country has been investing in the development of hydrogen-powered buses, trucks, and even trains. The goal is to reduce emissions in the transportation sector and promote the adoption of hydrogen-powered vehicles.
- Industrial Applications: China is exploring the utilization of hydrogen in various industries, including steel, chemicals, and refining. Green hydrogen can be used as a reducing agent or feedstock in these sectors, replacing fossil fuels and reducing carbon emissions. China's focus on hydrogen in industries aligns with its broader efforts to achieve carbon neutrality.

12. Russian Federation:
    - Natural Gas Resources: The Russian Federation has abundant natural gas reserves, which can be used as a feedstock for hydrogen production. The country is exploring the production of blue hydrogen by reforming natural gas with carbon capture and storage (CCS) technologies. This approach can reduce the carbon footprint of hydrogen production in the country.
    - Industrial Applications: Russia is exploring the utilization of hydrogen in industries such as steel and chemicals. Hydrogen can be used as a reducing agent in steelmaking, replacing coal or coke. The use of hydrogen in these industries can help reduce greenhouse gas emissions and support Russia's climate goals.
    - Research and Development: Russia is actively involved in the research and development of advanced electrolysis technologies for green hydrogen production. This includes exploring high-temperature electrolysis and solid oxide electrolysis cells (SOEC), which can enhance the efficiency and cost effectiveness of hydrogen production.
13. South Africa:
    - Renewable Energy Potential: South Africa has significant renewable energy resources, including solar and wind power. The country is exploring the production of green hydrogen through electrolysis powered by renewable energy sources. This can enable the utilization of renewable energy surpluses and support the transition to a low-carbon economy.
    - Industrial Decarbonization: South Africa is exploring the use of green hydrogen in industries such as mining and steel. By replacing fossil fuels with green hydrogen, these industries can reduce their carbon emissions and contribute to sustainable development. The use of green hydrogen as a reducing agent in steelmaking, for example, can help decarbonize the steel industry.
    - Power Generation and Energy Storage: South Africa is investigating the use of green hydrogen for power generation and energy storage. Hydrogen can be used in fuel cells to generate electricity, providing clean and reliable power. Additionally, excess renewable energy can be used to produce hydrogen, which can then be stored and converted back to electricity when needed, supporting grid stability and energy storage.

4.1.2. Industries

1. Transportation: The transportation sector is increasingly adopting green hydrogen as a zero-emission fuel. Fuel cell electric vehicles (FCEVs) powered by hydrogen are being developed and deployed by automakers such as Toyota, Hyundai, and BMW. There are also initiatives to use hydrogen for heavy-duty vehicles, buses, and trains.
2. Power Generation: Green hydrogen can be used in power plants to generate electricity with zero carbon emissions. Hydrogen can be combusted directly in gas turbines or used in fuel cells to produce electricity. Several countries are exploring the use of hydrogen in their power generation mix to decarbonize the electricity sector.

3. Industrial Applications: Industries such as steel, chemicals, and refineries are exploring the use of green hydrogen to decarbonize their processes. Hydrogen can be used as a feedstock, a reducing agent, or a source of heat in various industrial applications. Pilot projects and collaborations are underway to integrate hydrogen into industrial processes and reduce carbon emissions.
4. Energy Storage: Green hydrogen can be stored and used as a form of energy storage, helping to balance intermittent renewable energy sources. Excess renewable energy can be used to produce hydrogen through electrolysis, which can then be stored and converted back to electricity or other forms of energy when needed.
5. Refining and Petrochemicals: The refining and petrochemical industries are exploring the use of green hydrogen to reduce carbon emissions. Hydrogen can be used as a cleaner alternative to fossil fuels in various refining processes, such as desulfurization and hydrocracking. The transition to green hydrogen in these industries can help decarbonize their operations and reduce their environmental footprint.
6. Aviation: The aviation industry is investigating the use of green hydrogen as a sustainable fuel for aircraft. Hydrogen-powered aircraft, either through combustion or fuel cells, have the potential to significantly reduce greenhouse gas emissions compared to traditional jet fuels. Several companies and research institutions are working on developing hydrogen-powered aircraft and infrastructure.
7. Residential Heating: Green hydrogen can be used for residential heating applications, replacing natural gas or other carbon-intensive fuels. Hydrogen boilers and fuel cells can provide heat and hot water with zero carbon emissions. Pilot projects are underway in various countries to explore the feasibility and effectiveness of using hydrogen for residential heating.
8. Energy Export: Countries with abundant renewable energy resources, such as Australia and Chile, are exploring the export of green hydrogen to international markets. Green hydrogen can be transported as a commodity in the form of compressed or liquefied hydrogen, enabling countries to share their renewable energy potential with regions that have limited renewable resources.
9. Energy Storage and Grid Balancing: Green hydrogen can play a crucial role in energy storage and grid balancing. Excess renewable energy can be used to produce hydrogen through electrolysis during periods of low demand. The hydrogen can be stored and then converted back to electricity through fuel cells or combustion when demand exceeds supply, helping to stabilize the grid and ensure a reliable energy supply.

These examples highlight the diverse range of countries and industries that are actively involved in the production and utilization of green hydrogen. The global momentum toward green hydrogen is driven by the recognition of its potential to decarbonize various sectors and contribute to a more sustainable and cleaner energy future.

4.2. Green Hydrogen Production Using Renewable Energy

Here's a brief overview of green hydrogen production using renewable energy in the leading countries in this field [43–46].

Germany: Germany has been actively promoting the production of green hydrogen using renewable energy sources. The country has a strong focus on wind and solar power. Germany has set targets to increase renewable energy capacity and develop electrolysis facilities for green hydrogen production. Several projects are underway, including the construction of large-scale electrolyzes powered by renewable energy.

Australia: Australia has significant potential for green hydrogen production using its abundant solar and wind resources. The country is actively pursuing the development of renewable energy-powered electrolysis facilities. Australia aims to become a major exporter of green hydrogen, leveraging its renewable energy advantage and proximity to Asian markets.

Japan: Japan is a key player in the green hydrogen sector. The country has set ambitious targets for the development of a hydrogen society, including the production of green hydrogen using renewable energy. Japan is investing in large-scale electrolysis facilities powered by solar and wind energy. The government is also promoting international collaborations for the import and utilization of green hydrogen.

Netherlands: The Netherlands is actively pursuing green hydrogen production using renewable energy sources. The country has a strong focus on offshore wind power. The Dutch government has initiated projects to develop offshore wind farms that will directly supply electricity to electrolysis facilities for green hydrogen production. The Netherlands aims to become a hub for green hydrogen production, import, and distribution.

United States: The United States is rapidly increasing its efforts in green hydrogen production using renewable energy. The country has vast renewable energy resources, including solar, wind, and hydropower. Several states have launched initiatives to develop large-scale electrolysis facilities powered by renewable energy sources. The U.S. government is also supporting research and development and providing incentives to accelerate green hydrogen deployment.

Chile: Chile has abundant solar and wind resources, making it well-suited for green hydrogen production using renewable energy. The country has ambitious goals to become a leading producer and exporter of green hydrogen. Chile is focusing on developing large-scale electrolysis facilities powered by renewable energy sources. The government is also promoting the use of green hydrogen in industries like mining and transportation.

Saudi Arabia: Saudi Arabia, known for its vast oil reserves, is also investing in green hydrogen production using renewable energy. The country has substantial solar potential and is developing large-scale renewable energy projects. Saudi Arabia aims to leverage its renewable energy capacity for green hydrogen production through electrolysis. The government has plans to integrate green hydrogen into various sectors, including transportation and industry.

South Korea: South Korea is actively pursuing green hydrogen production using renewable energy sources, such as solar and wind power. The country has set ambitious targets for hydrogen deployment and is investing in the development of large-scale electrolysis facilities powered by renewable energy. South Korea is focusing on building a hydrogen economy and promoting the use of green hydrogen in transportation, industry, and power generation.

India: In India, green hydrogen production using renewable energy sources like solar and wind power is gaining momentum. The government has initiated projects to establish large-scale electrolysis facilities powered by renewable energy. These facilities use electricity from solar or wind farms to split water into hydrogen and oxygen through electrolysis, producing green hydrogen.

Canada: Canada has abundant renewable energy resources, such as hydro, wind, and solar power. The country is leveraging these resources to produce green hydrogen through electrolysis. Several projects are underway to develop electrolysis facilities powered by renewable energy sources. These facilities use electricity generated from renewables to produce green hydrogen from water.

China: China is investing in the production of green hydrogen using renewable energy sources. The country has been scaling up the deployment of wind and solar power, which can provide clean electricity for electrolysis. Large-scale electrolysis facilities powered by renewable energy are being developed to produce green hydrogen from water, contributing to China's hydrogen economy goals.

Russian Federation: The Russian Federation is exploring green hydrogen production using renewable energy, although its focus is more on blue hydrogen produced from natural gas with carbon capture and storage (CCS). However, the country is also involved in research and development of advanced electrolysis technologies powered by renewable energy sources to produce green hydrogen.

South Africa: South Africa has significant renewable energy potential, particularly in solar and wind power. The country aims to utilize this renewable energy to produce green hydrogen through electrolysis. Electrolysis facilities powered by renewable energy sources are being developed to produce green hydrogen from water, supporting the country's transition to a low-carbon economy.

4.3. Green Hydrogen Application in Different Industries

Green hydrogen has diverse applications across various industries. In the transportation sector, it can be used as a fuel for fuel cell vehicles, offering zero-emission transportation and reducing reliance on fossil fuels. In industry, green hydrogen can be utilized as a feedstock for chemical processes, enabling the production of green chemicals and materials. It can also be used in refineries, steel production, and other industrial processes to replace fossil fuels and reduce carbon emissions. Green hydrogen has applications in power generation, where it can be used in gas turbines or fuel cells to produce electricity, providing a clean and renewable energy source. Additionally, it can be used for residential and commercial heating, replacing natural gas or other fossil fuel-based heating systems. These applications demonstrate the versatility of green hydrogen and its potential to decarbonize multiple sectors of the economy [47–50].

Table 2 summarizes the green hydrogen production and utilization, as well as its application in different industries, in the leading countries in this field.

Table 2. Summary of green hydrogen application in different industries in the leading countries in this field.

Country	Green Hydrogen Production	Green Hydrogen Utilization	Industries Utilizing Green Hydrogen
Germany	Increasing capacity	Growing adoption	Steel, chemicals, refineries, transportation
Australia	Expanding production	Export ambitions	Transportation, industry, export markets
Japan	Scaling up production	Diverse applications	Transportation, power generation, industry, residential heating
Netherlands	Offshore wind integration	Building infrastructure	Transportation, industrial processes, power generation
United States	Rapidly increasing	Developing markets	Transportation, power generation, industry, heating and cooling
Chile	Developing capacity	Mining industry	Mining operations, heavy-duty vehicles, industrial applications
Saudi Arabia	Investing in production	Industrial applications	Petrochemicals, ammonia production, transportation
South Korea	Expanding production	Developing hydrogen economy	Transportation, power generation, industry, heating, and cooling
India	Expanding production	Transportation, power generation, industry	Transportation, power generation, industry, heating, and cooling
Canada	Growing production	Transportation, industry, export markets	Transportation, industry, export markets, power generation
China	Scaling up production	Transportation, power generation, industry	Transportation, power generation, industry, heating, and cooling
Russian Federation	Developing capacity	Transportation, industry, power generation	Transportation, industry, power generation
South Africa	Early-stage development	Transportation, mining industry	Transportation, mining industry, industrial applications

4.4. Key Aspects of the Benefits of Green Hydrogen Production and Utilization

The key aspects of the benefits of green hydrogen production and utilization are summarized in this section. These aspects highlight how green hydrogen production and utilization contribute to a sustainable, low-carbon energy system, offering environmental, economic, and energy security benefits. By harnessing the benefits of green hydrogen, we can accelerate the transition to a sustainable, low-carbon energy system and address the challenges posed by climate change and environmental degradation [51–54].

Figure 4 provides an overview of the important facets of green hydrogen production and utilization. As research, development, and investments in this field gain momentum, the potential for green hydrogen to play a vital role in fostering a sustainable and low-carbon energy landscape continues to expand. The examples presented here highlight the ongoing progress and applications in green hydrogen production and utilization. The diverse range of potential uses, coupled with the ongoing research efforts and investment initiatives, underscore the growing significance of green hydrogen as a pivotal element in driving the transition towards cleaner energy sources. These examples merely scratch the surface of the vast opportunities presented by green hydrogen. The continuous research, technological advancements, and increasing global interest in hydrogen further illustrate its potential to revolutionize multiple sectors and contribute to a more sustainable and environmentally friendly future.

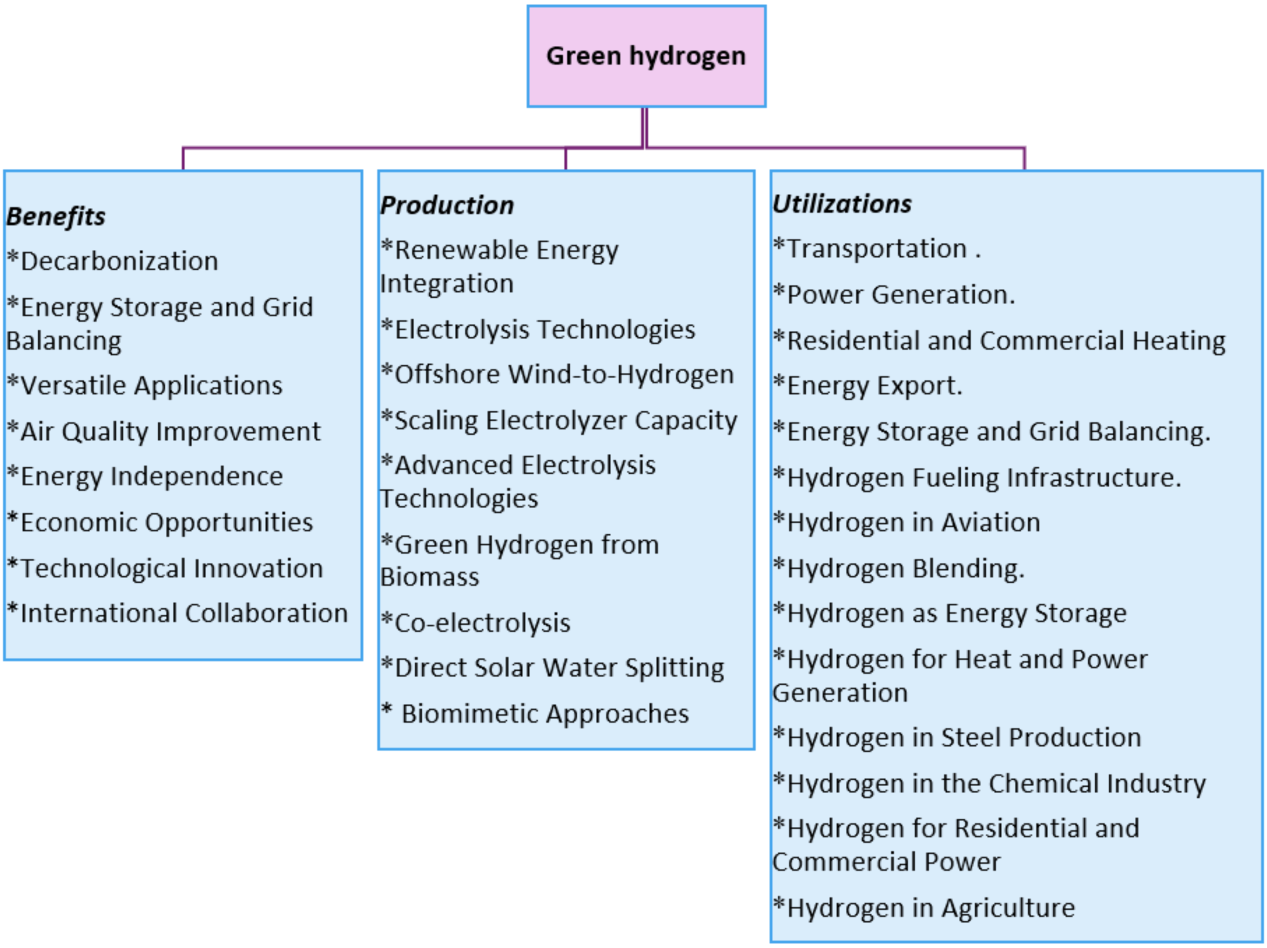

Figure 4. Green hydrogen benefits, production and utilization.

5. Innovative Methods of Producing and Using Green Hydrogen

Here are some additional details on the innovative methods of producing and using green hydrogen [51]:

1. Power-to-Gas (P2G): P2G technology allows for the conversion of excess renewable energy into hydrogen. When the supply of renewable energy exceeds the demand, the surplus electricity is used to power electrolyzes, which split water into hydrogen and

oxygen. The produced hydrogen can be stored and used later when renewable energy generation is low or as a clean fuel for transportation, heating, or industrial processes.

2. Biomass Conversion: Biomass can be converted into hydrogen through gasification or pyrolysis processes. Gasification involves heating biomass in a controlled environment to produce a synthesis gas (syngas) consisting of hydrogen, carbon monoxide, and other gases. The syngas can then be further processed to extract hydrogen. Pyrolysis, on the other hand, involves heating biomass in the absence of oxygen, which produces bio-oil, syngas, and char. Hydrogen can be extracted from the syngas component.
3. Photo Electrochemical (PEC) Water Splitting: PEC water splitting utilizes specialized semiconductor materials to directly convert solar energy into hydrogen. These materials are capable of absorbing sunlight and initiating the water-splitting reaction within the cell, generating hydrogen and oxygen. PEC technology offers the potential for efficient and direct solar-driven hydrogen production, eliminating the need for external electricity sources.
4. Hydrogen Fuel Cells: Hydrogen fuel cells are devices that generate electricity through an electrochemical reaction between hydrogen and oxygen. Hydrogen is supplied to the anode and oxygen (usually from the air) is supplied to the cathode of the fuel cell. The reaction produces electricity, heat, and water as byproducts. Fuel cells are a versatile technology that can be used in various applications, including transportation (e.g., fuel cell vehicles) and stationary power generation for buildings or remote off-grid locations.

These are just a few examples of innovative methods being explored for green hydrogen production and utilization. Researchers and scientists worldwide are actively investigating and developing new technologies, materials, and processes to enhance the efficiency, scalability, and cost effectiveness of green hydrogen production, storage, and usage. By continuously advancing these methods, the aim is to facilitate the widespread adoption of green hydrogen as a sustainable energy solution.

5. Electrolysis: Electrolysis is a process that uses electricity to split water molecules into hydrogen and oxygen. By passing an electric current through water, the hydrogen ions (H+) are attracted to the negative electrode (cathode), where they gain electrons to form hydrogen gas (H2). Oxygen is simultaneously produced at the positive electrode (anode). When the electricity used in the electrolysis process comes from renewable energy sources such as solar or wind, electrolysis can be a green and sustainable method of hydrogen production [52].
6. Plasma Arc Decomposition: Plasma arc decomposition, also known as plasma reforming, involves the use of high temperatures generated by an electric arc to break down natural gas (methane) into hydrogen and carbon monoxide. The process occurs in a plasma reactor, where the intense heat dissociates the methane molecules, releasing hydrogen gas. If the electricity used for the plasma arc decomposition is generated from renewable sources, this method can be considered a green hydrogen production method.
7. Thermolysis: Thermolysis is a hydrogen production method that involves the decomposition of a chemical compound, such as water or hydrocarbons, through the application of heat. By subjecting the compound to high temperatures, the molecular bonds are broken, resulting in the release of hydrogen gas. The heat required for thermolysis can be obtained from renewable energy sources to ensure the production process is environmentally friendly.
8. Thermochemical Processes: Thermochemical processes utilize chemical reactions and heat to produce hydrogen. These processes typically involve the use of metal oxides or metal hydrides as catalysts. During the thermochemical reactions, the catalysts absorb heat and undergo chemical transformations, releasing hydrogen gas as a byproduct. Thermochemical processes offer the potential for efficient hydrogen production, especially when coupled with renewable energy sources.
9. Hybrid Thermochemical Cycles: Hybrid thermochemical cycles combine different thermochemical reactions to achieve efficient hydrogen production. These cycles often involve

multiple steps, including the use of high temperatures, chemical reactions, and catalysts. By coupling different reactions and optimizing the cycle, hybrid thermochemical processes aim to improve the overall efficiency and feasibility of hydrogen production.

10. Photo-Electrolysis: Photo-electrolysis involves using sunlight to drive the electrolysis process for hydrogen production. Specifically, specialized semiconductor materials are used as photo electrodes to absorb sunlight and directly convert solar energy into electricity, which is then used to split water into hydrogen and oxygen. Photo-electrolysis offers the potential for direct and sustainable solar-driven hydrogen production.
11. Artificial Photosynthesis: Artificial photosynthesis is an emerging field that seeks to replicate the process of natural photosynthesis in plants to produce hydrogen. It involves using specialized materials and catalysts to capture sunlight and initiate chemical reactions that produce hydrogen from water. Artificial photosynthesis holds promise for renewable and sustainable hydrogen production, but it is still an area of ongoing research and development.

These methods showcase the diversity of approaches being explored to produce hydrogen using green energy sources and sustainable processes. Each method has its own advantages, challenges, and potential for further development and optimization.

6. Green Hydrogen Challenges, Recommendations, Expectations and Observations

6.1. Challenges

Some references [53–59] indicate that there are challenges and difficulties in implementing green hydrogen as a fuel. Here are some key points:

- Hydrogen Energy Loss: Implementation of green hydrogen is associated with a loss of about 30% of its energy content due to hydrogen liquefaction. This means that each unit of hydrogen produced equals only 70% of the available energy.
- Storage of Liquid Hydrogen (LH2): Storing liquid hydrogen is challenging due to the low storage temperature required (−253 °C under 1 bar) and the need for an effective isolation system.
- Hydrogen Safety: Because of hydrogen's flammability and potential for dilution of oxygen, hydrogen can pose a threat to human safety.
- High energy density: Hydrogen has a wide combustible limit range, low boiling point, low temperature, rate, content and flash rate. In addition, the heating value of hydrogen (LHV) is as low as 120 MJ/kg, which is three times the heating value of heavy fuel oil. This high energy density must be handled carefully to avoid accidents.
- Technical Challenges: Green hydrogen technology faces technical difficulties associated with high temperature and high pressure, which makes its storage difficult.
- Cost: The cost of hydrogen gas must be reduced to be competitive. Achieving a cost of USD 2 per kilogram is a competitive goal.
- Electricity Demand: The production and application of green hydrogen requires a large amount of electricity. To support these applications, renewable energy production such as offshore wind and solar energy must be increased.
- Offshore Wind Capacity: support is needed for such an application. Therefore, in the next 30 years, and every year, offshore wind energy should be developed more than in the last 20 years.
- Infrastructure: The establishment of a comprehensive infrastructure for the production, storage, transportation, and distribution of green hydrogen is a significant challenge. It requires the development of hydrogen production facilities, hydrogen refueling stations, and pipelines or other means of transporting hydrogen to end-users.
- Scaling Up Production: Scaling up the production of green hydrogen to meet the demand for various sectors such as transportation, industry, and power generation poses a challenge. Currently, the production of green hydrogen is limited, and significant investments and advancements are required to increase production capacity.
- Electrolysis Technology: The primary method for producing green hydrogen is through electrolysis, which involves using electricity to split water molecules into

hydrogen and oxygen. The efficiency and cost effectiveness of electrolysis technology need further improvements to make green hydrogen more commercially viable.
- Availability of Renewable Energy: The production of green hydrogen relies on a consistent and abundant supply of renewable energy sources such as wind and solar power. However, the intermittent nature of these energy sources poses challenges in ensuring a continuous and reliable supply of electricity for hydrogen production.
- International collaboration: The implementation of green hydrogen requires international collaboration and cooperation due to the global nature of the energy transition. Harmonizing standards, sharing best practices, and establishing cross-border infrastructure are essential for the widespread adoption of green hydrogen.
- Regulatory Rramework: Developing a supportive regulatory framework is crucial for the successful deployment of green hydrogen. This includes policies and incentives that promote investment in green hydrogen projects, facilitate research and development, and address safety and environmental concerns.
- Public awareness and acceptance: Promoting public awareness and acceptance of green hydrogen is vital. Educating the public about the benefits and potential of green hydrogen, addressing safety concerns, and fostering a positive perception of hydrogen as a clean energy source are important for its widespread adoption.

It is important to note that while there are challenges associated with green hydrogen, significant progress is being made in research, technology development, and investment to overcome these obstacles and accelerate the adoption of green hydrogen as a sustainable energy solution.

6.2. Recommendations

Below are some important recommendations that reflect several key aspects of promoting clean hydrogen [60–65].

- Consider Hydrogen as Part of Energy Transition Efforts: It is true that green hydrogen can be a sustainable solution in the long run. There should be a focus by the government and the private sector on supporting the green hydrogen market and promoting its use in various sectors such as transportation, industry and energy.
- Focusing on Green Hydrogen as a Long-Term Supply Option: It is clear that producing green hydrogen based on renewable energy is a sustainable option in the long term. Governments and companies should focus on developing these technologies, enhancing their availability and reducing their production costs to make green hydrogen more competitive.
- Comprehensive integration: It is true that the various aspects of integration in the hydrogen value chain deserve special attention. From production to distribution, storage and use, the integration of all these processes must be enhanced to achieve maximum efficiency and environmental benefits.
- Ensure Efficient Supply and Use of Hydrogen: Appropriate technology and infrastructure must be developed to deal with storage and transportation losses and achieve the highest efficiency in hydrogen use. Advanced and innovative storage and transportation technology can contribute to this goal. Therefore, joint action between governments, companies and the international community must continue to promote the use of clean hydrogen and achieve a sustainable energy transition.

Some countries have leadership in producing green hydrogen and promoting its use as part of their efforts to achieve environmental sustainability and diversify energy sources. Here are some of the leading green-hydrogen-producing countries:

- Japan: Japan is considered one of the leading countries in the field of green hydrogen. Japan aims to achieve a hydrogen-based society by 2050, and is investing in developing the technology and infrastructure needed to produce and use green hydrogen.

- Germany: Germany is making ambitious plans to promote green hydrogen as part of its energy strategy. The German government is promoting the production and sustainable use of green hydrogen in sectors such as transport and industry.
- The Netherlands: The Netherlands seeks to become one of the leading countries in the production of green hydrogen. The Netherlands is investing in green hydrogen projects and working to provide the necessary infrastructure to promote the use of green hydrogen in transport and industry.
- South Korea: South Korea is one of the leading countries in the field of green hydrogen. South Korea is investing in developing technology related to green hydrogen and aims to increase its use in transportation and industry. These countries are making significant investments in developing technology and infrastructure related to green hydrogen, and are expected to continue to make significant progress in this field in the coming years.

6.3. Expectations

The demand for clean hydrogen is expected to grow exponentially by sector from 2030 to 2050. According to projections, achieving net zero greenhouse gas emissions by 2050 will require developing a clean hydrogen market of up to 170 Mtph by 2030. It is It is expected to continue to grow, reaching nearly 600 million metric tons per hour by 2050 [66]. In 2019, more than 85% of global electricity consumption (22,850 TWh) depended on fossil fuels [67]. At present, the clean hydrogen market cannot compete with fossil fuels economically, as fossil fuel prices rarely reflect external environmental costs. However, this dynamic is expected to change with the passage of time and the development of technology and the reduction of costs of producing and using clean hydrogen. Increasing demand for clean hydrogen requires advanced infrastructure, efficient production and storage technologies, and lower costs. Governments and companies are expected to invest in research and development and foster innovation to boost the clean hydrogen market and make it more economically competitive [68]. Clean hydrogen technology is being developed, such as desalination technologies to obtain hydrogen and technologies for safely storing and transporting hydrogen. Early steps in market trials and applications of clean hydrogen in high consumption industries may play an important role in increasing demand and developing the market. In the long term, clean hydrogen is expected to be a sustainable and efficient alternative to fossil fuels in many sectors such as transportation, industry and electricity production [69].

Figure 5 shows that clean hydrogen can play an important role in many industrial sectors and in the energy system in general. Here are some key points to note:

- Industries such as the iron and steel industry and the chemical industry can benefit from using clean hydrogen to decarbonize production processes and reduce emissions. Pure hydrogen can be used as a reducing agent in the steel industry, and it can also be used as an energy source in other high-temperature industrial applications.
- In the transportation sector, clean hydrogen can be used in fuel cells or internal combustion engines to power vehicles. Pure hydrogen is considered a supplement to electric vehicles in the field of long-distance charging.
- Hydrogen can play an important role in the energy system as energy storage and resilience services. Hydrogen can be produced from excess electricity generated from renewable sources, and stored for use in periods of excess demand [70].
- Hydrogen can also be injected into the existing natural gas transmission and distribution network as a potential alternative to reducing carbon emissions in building gas consumption [71]. However, it should be noted that these prospects and potential uses of clean hydrogen are dependent on technology development, availability of adequate infrastructure, and costs of production and use [72].

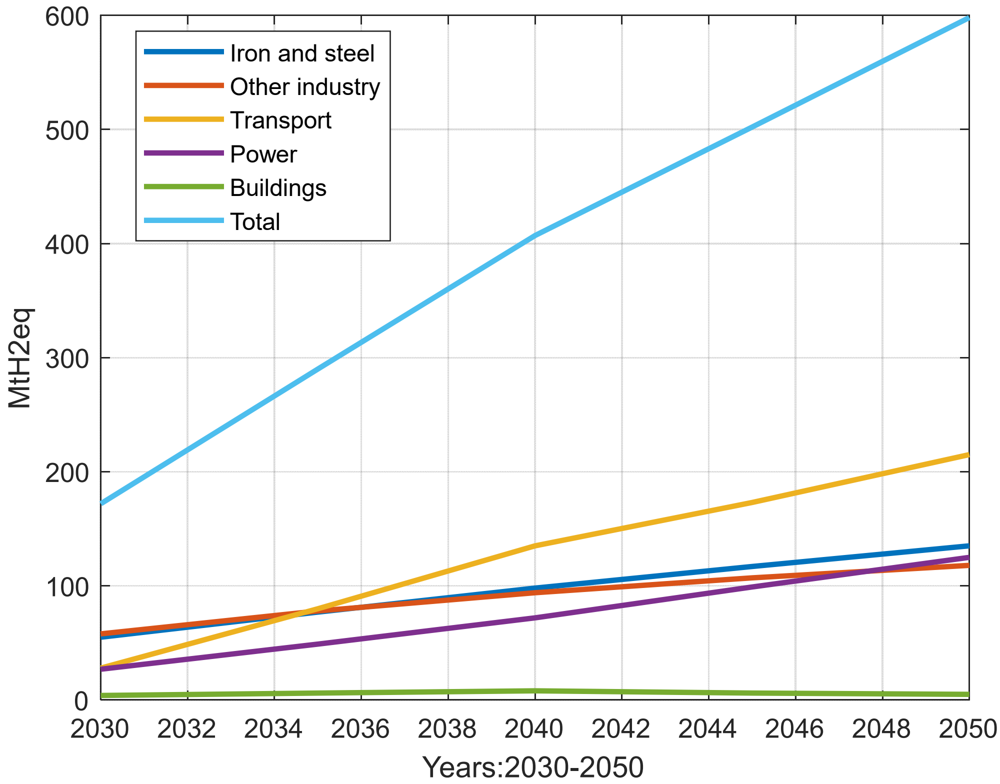

Figure 5. Evolution of clean hydrogen demand by sector, 2030 to 2050 (MtH2eq).

Estimates and forecasts may vary between different sources, and depend on multiple factors such as government policies, available technology, and changes in demand and supply over time.

6.4. Observations

The topic "green hydrogen: integrating renewable and sustainable energy into the energy future" holds significant importance in the context of transitioning to a sustainable and low-carbon energy system. Here are some observations that may be beneficial to readers [73]:

- Potential and Benefits: Green hydrogen has the potential to play a crucial role in integrating renewable energy sources into the energy future. It offers a versatile and carbon-neutral energy carrier that can be produced using renewable electricity. The integration of green hydrogen can help address the intermittency and storage challenges associated with renewables, thereby enabling a more reliable and resilient energy system.
- Environmental Impact: Green hydrogen production offers a sustainable alternative to conventional hydrogen production methods, which often rely on fossil fuels. By utilizing renewable energy sources, green hydrogen can significantly reduce greenhouse gas emissions, air pollution, and dependence on finite fossil fuel resources.
- Technological Advancements: Ongoing research and development efforts are focused on improving the efficiency and cost effectiveness of green hydrogen production, storage, and utilization technologies. Advancements in electrolysis technology, catalysts, and infrastructure development are key areas of progress that will further enhance the viability of green hydrogen as a mainstream energy solution.
- Infrastructure Requirements: The widespread adoption of green hydrogen would necessitate the development of a robust infrastructure, including hydrogen production facilities, storage systems, and distribution networks. Collaboration among governments, industries, and research institutions is essential to facilitate the necessary investments and infrastructure planning.

- Economic Viability: While the costs of green hydrogen production have been decreasing, further efforts are needed to make it economically competitive with conventional energy sources. Technological advancements, economies of scale, and supportive policies can contribute to reducing the costs and enhancing the economic feasibility of green hydrogen.
- Policy and Regulatory Support: Governments play a pivotal role in creating a favorable environment for the growth of green hydrogen. Supportive policies, such as financial incentives, research funding, and carbon pricing mechanisms, can accelerate the deployment of green hydrogen technologies and stimulate market demand.
- Collaboration and Knowledge Sharing: Collaboration among stakeholders, including researchers, policymakers, industries, and communities, is vital for the successful integration of green hydrogen into the energy future. Sharing knowledge, best practices, and lessons learned from pilot projects and real-world deployments can facilitate the widespread adoption of green hydrogen technologies.

Thus, the topic of green hydrogen integration into the energy future offers promising opportunities for a clean and sustainable energy transition. However, it requires concerted efforts from various stakeholders, technological advancements, supportive policies, and investments to overcome challenges and fully realize its potential.

Certainly, here are some additional points for further evaluation and observations regarding the topic of green hydrogen integration into the energy future:

- Scalability and Deployment: As green hydrogen technologies continue to develop, it is essential to assess their scalability and deployment potential. Scaling up production, storage, and distribution infrastructure to meet increasing demand will require careful planning and coordination among stakeholders. Identifying suitable locations for large-scale green hydrogen projects and optimizing supply chains will be critical for successful deployment.
- Energy Transition Synergies: Green hydrogen can contribute to the broader energy transition by integrating with other renewable energy technologies and systems. For example, coupling green hydrogen production with wind or solar farms can help balance electricity supply and demand, maximize renewable energy utilization, and provide additional revenue streams for renewable energy project developers.
- Technological Challenges: Despite advancements, there are still technological challenges that need to be addressed. For instance, improving the efficiency of electrolysis processes, reducing the cost of catalyst materials, and enhancing hydrogen storage methods are areas that require ongoing research and development efforts. Innovations in these areas can further enhance the viability and competitiveness of green hydrogen.
- International Collaboration: Given the global nature of climate change and energy transition, international collaboration is crucial. Sharing best practices, research findings, and collaborating on joint projects can accelerate the development and deployment of green hydrogen technologies. International agreements and partnerships can also facilitate cross-border trade and cooperation, driving the growth of a global green hydrogen market.
- Social and Economic Implications: The transition to a green hydrogen-based energy system will have social and economic implications. It has the potential to create new job opportunities, particularly in industries related to green hydrogen production, infrastructure development, and hydrogen-based applications. However, it is important to ensure a just transition, providing support for affected communities and workers in fossil fuel-dependent industries.
- Public Awareness and Acceptance: Public awareness and acceptance of green hydrogen will play a crucial role in its successful integration. Educating the public about the benefits, potential applications, and environmental impacts of green hydrogen can foster support and drive consumer demand. Transparent communication about safety measures and addressing any misconceptions can also instill confidence among stakeholders.

- Life Cycle Assessment: Conducting a comprehensive life cycle assessment of green hydrogen is essential to evaluate its overall environmental impact. This assessment should consider the entire life cycle, including the production, distribution, and utilization stages, to determine its carbon footprint and potential environmental benefits compared to conventional energy sources.

As result, the topic of green hydrogen integration into the energy future represents a transformative opportunity to decarbonize the energy sector and advance sustainability goals. By critically evaluating various aspects, including scalability, technological challenges, social and economic implications, and international collaboration, stakeholders can gain a holistic understanding of the potential benefits and challenges associated with green hydrogen. This knowledge will aid in making informed decisions and formulating effective strategies to drive the successful integration of green hydrogen into the energy landscape [74].

Here are some economical means of green hydrogen production and potential utilization strategies [75,76]:

- Electrolysis with Renewable Energy Sources: One of the most economical methods of green hydrogen production is through electrolysis powered by renewable energy sources such as solar, wind, or hydroelectric power. By utilizing abundant and low-cost renewable energy, electrolysis can produce green hydrogen with minimal carbon emissions. This method can be properly utilized by strategically locating electrolysis facilities near renewable energy generation sites, optimizing the use of excess renewable energy during off-peak hours, and implementing grid-balancing strategies.
- Biomass Gasification: Biomass gasification is another cost-effective method for green hydrogen production. Biomass feedstocks, such as agricultural residues or dedicated energy crops, can be gasified to produce a syngas, which is then converted into hydrogen through various processes. This method offers the advantage of utilizing organic waste materials and providing an additional revenue stream for the agricultural sector. Proper utilization involves establishing biomass supply chains, optimizing gasification technologies, and ensuring sustainable sourcing practices.

In summary, the proper utilization of these economical methods of green hydrogen production, such as electrolysis with renewable energy sources and biomass gasification, requires careful planning, technology optimization, infrastructure development, and exploring potential markets and applications for green hydrogen.

7. Conclusions

This review clearly highlights the prominent position of green hydrogen within the realm of renewable and clean energy, emphasizing its substantial potential in attaining global environmental objectives and mitigating harmful emissions. Green hydrogen finds diverse applications as an energy source in industry, as well as in transportation and heating and cooling systems. It can be generated through various processes, encompassing oil distillation, coal mining, brackish water desalination, and natural gas conversion. Presently, there is a noticeable surge in interest worldwide regarding the production of green hydrogen, which is synthesized using renewable sources like solar energy, wind power, and hydropower. This variant is regarded as cleaner and more environmentally sustainable when compared to blue and yellow hydrogen derived from natural gas and coal. Several nations, including Japan, South Korea, China, the European Union, and the United States, have embraced plans for expanding hydrogen production in the future. These countries aspire to harness hydrogen as a clean and renewable energy source, actively striving to advance the requisite technology to achieve higher efficiency and reduced costs in green hydrogen production. Despite the existence of challenges pertaining to production costs, storage, and transportation, significant efforts are being made to overcome these obstacles and foster increased production of green hydrogen.

The integration of green hydrogen for sustainable energy presents both challenges and opportunities. By critically evaluating aspects such as environmental impact assessment, technological advancements, infrastructure development, policy frameworks, economic viability, and workforce transition, this article provides insights that will help navigate the complexities of integrating green hydrogen into the energy landscape. It is through careful consideration and collaboration that the full potential of green hydrogen can be realized, leading to a cleaner and more sustainable energy future.

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