Engineering and Technology Journal e-ISSN: 2456-3358
Volume 10 Issue 09 September-2025, Page No.- 6860-6871
DOI: 10.47191/etj/v10i09.11, I.F. – 8.482

Green Hydrogen Integration In Hybrid Renewable Energy Systems: A Solution For Decarbonizing Energy Supply Chains

Sadat Itohan Ihwughwavwe[1], Gloria Siwe Usiagu[2]
[1]Independent Researcher, Nigeria
[2]Shell Petroleum Development Company, Nigeria;

ABSTRACT: Integrating green hydrogen into hybrid renewable energy systems presents a promising pathway to decarbonizing energy supply chains and achieving global sustainability goals. Green hydrogen, produced via electrolysis powered by renewable energy sources, offers a versatile solution for addressing emissions in hard-to-electrify sectors such as heavy industry, transportation, and utilities. By coupling green hydrogen with renewable energy technologies like wind, solar, and hydro, hybrid systems can mitigate intermittency challenges, enhance grid stability, and enable long-term energy storage. This paper explores the potential of integrating green hydrogen into hybrid systems, examining key challenges such as technological limitations, economic feasibility, and regulatory hurdles. Furthermore, it discusses the opportunities for decarbonizing high-emission industrial sectors and the role of green hydrogen in energy storage and grid integration. Drawing from global case studies and initiatives, this paper highlights the advancements made in green hydrogen production, storage, and infrastructure development. The findings suggest that while significant challenges remain, the future of green hydrogen in hybrid renewable energy systems is promising, contingent on further technological innovation, policy support, and market solutions. Recommendations are provided for future research and policy development to accelerate the widespread adoption of green hydrogen and unlock its full potential in the energy transition.

KEYWORDS: green hydrogen, hybrid renewable energy systems, decarbonization, energy supply chains, energy storage, technological innovation

1. INTRODUCTION

1.1 Context and Importance

The transition toward sustainable energy is one of the most urgent challenges facing global economies today. As nations strive to meet ambitious climate goals, such as those outlined in the Paris Agreement, decarbonizing energy supply chains becomes critical in mitigating climate change and reducing global reliance on fossil fuels[1]. A key driver of this transformation is the increased use of renewable energy sources, which promise to reduce greenhouse gas emissions and support a cleaner, more sustainable future. However, despite significant advances in renewable energy technologies, challenges remain regarding storage, grid stability, and supply reliability[2].

One of the most promising solutions to these challenges is the integration of green hydrogen. Green hydrogen, produced through water electrolysis using renewable energy, offers a clean and flexible energy carrier that can be stored, transported, and used in various sectors[3]. By providing an effective means of decarbonizing hard-to-electrify sectors such as heavy industry, transportation, and long-term energy storage, green hydrogen has the potential to revolutionize energy supply chains[4]. This paper focuses on the role of green hydrogen in the integration of hybrid renewable energy systems, which combine various renewable energy sources to ensure a more reliable and resilient energy system.

1.2 Role of Green Hydrogen in Reducing Carbon Emissions

Green hydrogen has emerged as a key player in the global effort to decarbonize various sectors of the economy[5]. Unlike conventional hydrogen, which is typically produced from natural gas (a process that generates significant carbon emissions), green hydrogen is produced by splitting water molecules into hydrogen and oxygen using electricity generated from renewable energy sources such as wind, solar, or hydropower. As a result, green hydrogen is considered a "clean" fuel that produces no direct emissions during production or utilization[6].

The versatility of green hydrogen makes it an attractive option for a wide range of applications. It can be used as a fuel for transportation, replacing fossil fuels in vehicles, ships, and aircraft. It can also be utilized as a feedstock in industrial processes such as steel production, replacing coal and natural gas[7]. Additionally, green hydrogen has great potential as a long-term energy storage solution, addressing the intermittency challenges associated with renewable energy sources like solar and wind. By storing excess renewable energy as hydrogen during periods of high production and using it when renewable generation is low, hydrogen can help stabilize the grid and provide a continuous, low-carbon energy supply[8].

The growing focus on green hydrogen reflects its central role in achieving carbon neutrality by mid-century. Green hydrogen may be the only viable option for reducing emissions and achieving the necessary decarbonization levels for many industries and sectors. As such, its integration into energy supply chains represents a critical step toward the global goal of limiting global temperature rise and achieving sustainable development[9].

1.3 Hybrid Renewable Energy Systems and Their Role in the Energy Transition

Hybrid renewable energy systems are gaining increasing attention as effective solutions to the challenges of renewable energy intermittency and variability. These systems integrate multiple renewable energy sources, such as wind, solar, and hydropower, to create a more reliable and resilient energy supply. By combining different technologies, hybrid systems can provide consistent energy production by compensating for the inherent fluctuations in each renewable source[10].

Hybrid systems can be further enhanced by incorporating green hydrogen into their design. The combination of hydrogen production with renewable energy generation offers a powerful way to address several key challenges in the energy transition[11].For example, hybrid systems with integrated green hydrogen production can help balance supply and demand by storing excess energy in the form of hydrogen during times of low demand or high renewable generation. The stored hydrogen can then be converted back into electricity or used in other applications when demand is higher or renewable generation is low, effectively smoothing out the intermittent nature of renewable sources[12].

Moreover, hybrid systems are particularly valuable in regions with limited access to single renewable resources. By leveraging the complementary characteristics of multiple energy sources, such as the availability of wind energy at night or solar energy during the day, hybrid systems can increase the overall efficiency and reliability of the energy grid. In combination with green hydrogen, these systems can provide a stable and decarbonized energy supply, which is vital for achieving energy security, sustainability, and carbon neutrality[13].

In regions with varying renewable energy potentials, hybrid systems could also reduce the need for costly grid infrastructure and reliance on fossil fuels, making them an economically viable solution for energy transitions. Integrating green hydrogen into these hybrid systems can unlock additional value by providing a clean, storable, and transportable energy source that can support decarbonization efforts across a range of sectors[14].

1.4 Thesis Statement

This paper explores the potential of integrating green hydrogen into hybrid renewable energy systems as a solution to decarbonize energy supply chains. Specifically, it argues that hybrid systems incorporating green hydrogen production, storage, and utilization can be pivotal in achieving a sustainable energy transition. By addressing the intermittency of renewable energy sources, enhancing grid stability, and providing clean fuel for hard-to-electrify sectors, the integration of green hydrogen into hybrid systems offers a holistic approach to reducing carbon emissions across various industries and regions.

The paper will outline the current state of green hydrogen technology and hybrid energy systems, highlight the challenges associated with their integration, and discuss the opportunities that arise from their combination. A review of existing literature and case studies will demonstrate that green hydrogen is an essential component of energy decarbonization and a key enabler of energy resilience, flexibility, and sustainability. Ultimately, the paper will advocate for policies and technological advancements supporting the widespread adoption of green hydrogen in hybrid renewable energy systems, underscoring its crucial role in meeting global climate and energy goals.

By combining renewable energy technologies with green hydrogen, we can pave the way for a decarbonized future that ensures energy security, mitigates climate change, and supports the economic growth of a sustainable energy industry. The next sections of this paper will delve deeper into the background of these systems, the challenges they face, and the potential solutions for overcoming barriers to their widespread deployment.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Current Energy Supply Chain Challenges

The global energy supply chain faces significant challenges as the world seeks to transition from fossil fuels to more sustainable energy sources. The primary challenge is the high dependence on carbon-intensive energy generation methods, which are responsible for environmental degradation and geopolitical vulnerabilities, energy price volatility, and supply security risks[15]. Fossil fuel-based energy generation, especially coal, oil, and natural gas, still dominates the global energy mix, contributing significantly to greenhouse gas emissions and accelerating global warming[16].

In many regions, the energy infrastructure is outdated, inefficient, and heavily reliant on non-renewable energy sources, further complicating efforts to meet international climate targets[17]. Additionally, the transportation and storage of energy resources, such as crude oil, coal, and natural gas, pose logistical challenges and environmental risks, including pipeline ruptures, oil spills, and air pollution[18]. The global supply chain for fossil fuels is also subject to price fluctuations and market dynamics, which can disrupt energy availability and affordability[19].

The integration of renewable energy sources such as wind, solar, and hydropower presents a promising solution to these issues by reducing reliance on fossil fuels, lowering emissions, and offering a cleaner, more sustainable energy future[20]. However, renewable energy sources themselves bring their own challenges, particularly around intermittency and reliability. Wind and solar power, while abundant and clean, are highly variable, meaning their production cannot always align with demand. This intermittency can lead to grid instability, where excess energy is wasted during periods of high production, and shortages occur when generation is low[21].

Furthermore, while renewable energy technologies have made significant strides, they still require considerable investments in infrastructure, including energy storage, grid modernization, and flexible generation systems. Integrating renewables into the energy grid necessitates robust mechanisms for balancing supply and demand, ensuring that energy is always available, even when the sun is not shining or the wind is not blowing. This is where the role of green hydrogen and hybrid renewable energy systems becomes critical, providing solutions to address the inherent limitations of renewable energy sources while advancing the decarbonization agenda[22].

2.2 Green Hydrogen Production and Storage

Green hydrogen, often called the "fuel of the future," is produced through water electrolysis using renewable electricity from wind, solar, or hydropower. The electrolysis process involves passing an electric current through water, which separates the hydrogen and oxygen molecules. The hydrogen gas produced in this way is considered green because the electricity produced comes from renewable sources, ensuring that no greenhouse gas emissions are generated during the process[23].

The production of green hydrogen holds significant potential to decarbonize various sectors, including heavy industry (e.g., steel and cement production), transportation (e.g., fuel cells for vehicles, ships, and planes), and electricity generation[24]. It is seen as a vital component of future energy systems because it can be stored for long durations, providing a means of overcoming the intermittency associated with renewable energy sources. When combined with renewable energy generation, green hydrogen offers a way to store excess energy during periods of high generation, ensuring that it can be used later when energy demand is high or when renewable sources are unavailable[25].

However, while green hydrogen's potential is significant, several factors currently limit its production. The primary challenge is the cost of electrolysis technology, which remains high compared to conventional hydrogen production methods, such as steam methane reforming (SMR) that relies on fossil fuels. Electrolyzers, which are used in the process of electrolysis, are expensive and require substantial upfront investment, making green hydrogen production costly[26]. Additionally, the scalability of electrolyzers and the availability of renewable electricity are also limiting factors, as large-scale production requires significant amounts of renewable energy and infrastructure[27]. Storage and transportation of green hydrogen also present significant challenges. Hydrogen, the smallest and lightest molecule, has a low energy density, making it difficult to store and transport efficiently. Currently, hydrogen is stored either as a compressed gas or in liquid form, both of which require energy-intensive processes. The infrastructure needed to store and transport hydrogen, such as pipelines, tanks, and liquefaction facilities, is also costly and in the early stages of development. Moreover, the global hydrogen distribution network is still underdeveloped, with few international trade routes and storage hubs[28].

Despite these challenges, the potential for green hydrogen to play a critical role in energy transition and decarbonization is undeniable. Significant investments are being made in research and development to improve electrolyzers' efficiency, scalability, cost-effectiveness, storage solutions, and transportation infrastructure. Moreover, as renewable energy generation capacity continues to grow, green hydrogen production costs are expected to decrease, making it a more attractive option for wide-scale deployment[29, 30].

2.3 Hybrid Renewable Energy Systems

Hybrid renewable energy systems are designed to combine multiple renewable energy sources, such as wind, solar, and hydropower, to increase the reliability and efficiency of energy generation[31].These systems take advantage of the complementary nature of different energy sources, providing a more stable and consistent energy supply. For example, wind power is often abundant at night or during cloudy periods when solar power is not generating, while solar energy is typically highest during the day. By combining these sources, hybrid systems can help mitigate the intermittency of individual renewable technologies[10].

One of the key advantages of hybrid systems is that they can be deployed in a wide range of locations, including those with limited access to a single renewable resource. In regions with insufficient wind energy, solar power or hydropower can supplement energy generation, and vice versa. This flexibility makes hybrid systems particularly useful in addressing energy needs in remote or off-grid areas and regions with variable renewable energy potential.

Another important advantage of hybrid renewable systems is their ability to integrate energy storage technologies, such as batteries or green hydrogen. Storage is critical in ensuring that energy produced during periods of high renewable generation can be used during times of low production or high demand[32]. Green hydrogen, in particular, offers a unique advantage as an energy storage solution due to its ability to store large quantities of energy over long periods. By converting surplus renewable electricity into hydrogen through electrolysis, hybrid systems can effectively decouple energy production from energy consumption, enabling a continuous and reliable supply of clean energy[31].

The integration of green hydrogen into hybrid systems can further enhance the flexibility, resilience, and sustainability of energy supply chains. By producing hydrogen during periods of high renewable generation and storing it for later use, hybrid systems can help balance supply and demand, reduce reliance on fossil fuels, and support integrating more renewable energy into the grid. In addition, hydrogen can serve as a fuel for sectors that are difficult to electrify, such as heavy industry and transportation, making it a versatile and valuable energy carrier[33].

Regarding technology, hybrid systems typically rely on advanced control systems that optimize the integration of different energy sources and storage technologies. These control systems ensure that energy generation and storage are managed efficiently, maximizing the use of available renewable resources and minimizing waste. Additionally, hybrid systems often include backup generation capacity, such as natural gas or bioenergy, to ensure reliability during periods of low renewable generation[34].

The combination of hybrid systems and green hydrogen is a promising pathway for achieving a sustainable, decarbonized energy future. These systems can help overcome some of the key challenges associated with renewable energy, such as intermittency, energy storage, and sectoral decarbonization, while enhancing energy security and economic resilience.

2.4 Global Progress and Case Studies

Several countries and regions have already begun exploring and implementing the integration of green hydrogen into hybrid renewable energy systems. These early initiatives provide valuable insights into the potential of hydrogen as a key enabler of energy transition and decarbonization.

One notable example is the European Union, which has been at the forefront of hydrogen development through its Hydrogen Roadmap and various national initiatives. The EU aims to produce green hydrogen at scale, with a target of 10 million tons of hydrogen produced annually by 2030[35]. The EU is also investing in hydrogen hubs designed to integrate renewable energy generation with hydrogen production, storage, and distribution. For instance, the North Sea Wind Power Hub is a large-scale project that will combine offshore wind farms with green hydrogen production, creating a hydrogen export hub for Europe. This project is expected to significantly decarbonize Europe's energy supply and foster a green hydrogen economy[36].

In Australia, the Hydrogen Energy Supply Chain (HESC) project is one of the most ambitious efforts to produce and export green hydrogen. This project aims to produce hydrogen using brown coal and renewable energy in Victoria and export it to Japan. The project involves the construction of a hydrogen liquefaction facility, a transport network, and a distribution system. The success of this project could pave the way for the development of hydrogen hubs in other parts of the world, with the potential for hydrogen to become a key global energy commodity[37].

In the United States, the Department of Energy (DOE) has launched the Hydrogen Program to accelerate research and development in hydrogen production, storage, and utilization. The DOE's initiative includes funding various demonstration projects integrating green hydrogen with renewable energy systems[38]. One such project is the Tehachapi Energy Storage Project in California, which uses hydrogen as a storage medium to balance the output of wind and solar power. This project demonstrates how hydrogen can be used to store and release renewable energy, helping to ensure grid stability and supporting the energy sector's decarbonization[39].

These case studies highlight the growing momentum behind green hydrogen and its potential to transform energy supply chains. As research and development continue, more countries and regions will likely adopt similar strategies to integrate hydrogen into their renewable energy systems, unlocking new opportunities for decarbonization and sustainability.

3. CHALLENGES IN GREEN HYDROGEN INTEGRATION

3.1 Technical Barriers

One of the primary technical barriers to the widespread adoption of green hydrogen is the inefficiency and scalability of hydrogen production technologies[40]. Although electrolysis offers a promising pathway for green hydrogen production by using renewable electricity to split water molecules, the process is still less efficient and more expensive than conventional hydrogen production methods, such as steam methane reforming (SMR). The energy conversion efficiency of electrolyzers is a major concern; most commercial electrolyzers operate at an efficiency rate of approximately 60-70%, meaning a substantial amount of energy is lost in the process of producing hydrogen. This inefficiency raises the cost of hydrogen production and limits the environmental benefits of using renewable electricity to generate hydrogen, as the overall energy input must be high enough to make the process economically viable[41].

Moreover, scaling up the production of green hydrogen poses additional technical challenges. Electrolyzers must be manufactured in large quantities and at a cost-effective price, while maintaining performance standards over time[42]. Currently, most electrolyzer production is limited to small-scale systems or pilot projects, which makes the transition to large-scale production a significant hurdle. The ability to scale up electrolyzers efficiently and affordably will be crucial in achieving the volume of green hydrogen necessary to replace fossil fuels in various industries, such as transportation, heavy industry, and power generation[43].

Another major technical challenge is the storage and transportation of green hydrogen. Hydrogen is the lightest and smallest molecule, which makes it difficult to store and transport efficiently. Current storage methods involve either compressing hydrogen to extremely high pressures or liquefying it at very low temperatures[44]. Both of these methods are energy-intensive and costly, requiring advanced materials and technologies to ensure safety, efficiency, and reliability. Compressed hydrogen requires high-strength materials and robust infrastructure to prevent leakage and ensure safe storage, while liquefied hydrogen storage necessitates maintaining ultra-low temperatures, which demands substantial energy input.

The development of advanced storage technologies, such as solid-state hydrogen storage, liquid organic hydrogen carriers, or advanced cryogenic systems, is ongoing. These emerging technologies aim to provide safer, more efficient, and lower-cost solutions for hydrogen storage. However, these technologies are not yet widely available or commercially viable, and further research and development are needed to scale them up[45].

Furthermore, the integration of green hydrogen with existing infrastructure presents another significant technical challenge. Most of the current infrastructure for energy distribution, including pipelines, refueling stations, and power plants, is designed for fossil fuels[46]. Retrofitting or replacing these systems to accommodate hydrogen, especially in regions with extensive existing infrastructure, could require significant investments in new technology, equipment, and retrofitting. Hydrogen pipelines, in particular, present their own set of technical challenges, as hydrogen embrittlement can weaken metals and materials commonly used in natural gas pipelines, requiring the development of specialized materials capable of safely transporting hydrogen over long distances[47].

3.2 Economic Considerations

Beyond the technical hurdles, economic challenges play a crucial role in the integration of green hydrogen into energy systems. The high cost of producing green hydrogen compared to conventional hydrogen remains one of the largest obstacles to its widespread adoption. As of now, the production cost of green hydrogen is significantly higher than that of hydrogen produced from natural gas, primarily because the electrolysis process is energy-intensive and electrolyzers are expensive. While the cost of renewable energy has decreased significantly in recent years, the cost of green hydrogen remains high due to inefficiencies in electrolyzers and the need for substantial capital investments in infrastructure[48].

For green hydrogen to become economically viable, economies of scale must be realized. As electrolyzer production ramps up and technology improves, it is anticipated that the cost of green hydrogen will decrease. However, the current gap between the cost of green hydrogen and conventional hydrogen is still substantial, and there is uncertainty about how long it will take to close this gap. Moreover, subsidies or financial incentives may be required in the interim to make green hydrogen more competitive with other energy sources, such as natural gas or coal, which have lower production costs and longer-established infrastructure[49].

In addition to production costs, the economic feasibility of hybrid renewable energy systems that integrate green hydrogen is also a major consideration. Hybrid systems, which combine renewable energy sources like wind and solar with energy storage systems, including green hydrogen, require large-scale infrastructure investments, which can be prohibitively expensive.[50] The capital cost of setting up hybrid renewable energy systems, including purchasing and installing electrolyzers, storage facilities, and grid integration equipment, may discourage some investors, especially in regions where financial resources are limited or fossil fuel energy sources are subsidized[51].

The overall cost-effectiveness of hybrid renewable energy systems and green hydrogen integration is heavily influenced by factors such as energy demand, the availability of renewable resources, and regional infrastructure. In regions with abundant renewable energy resources, such as in parts of the Middle East, Australia, or sub-Saharan Africa, the economic case for green hydrogen integration may be more compelling due to low electricity costs. Conversely, in regions with limited access to renewable energy, the economic feasibility of large-scale hydrogen production and integration may be less attractive[52].

Despite these economic challenges, several strategies are being proposed to improve the cost-effectiveness of green hydrogen. Innovations in electrolyzer design, increased production scale, and improvements in renewable energy generation efficiency could reduce the overall costs of producing and integrating green hydrogen. Additionally, the development of hydrogen markets, including international trade and supply chains, could stimulate competition and lower costs, similar to how renewable energy markets have driven down the costs of solar and wind energy in recent years.

3.3 Regulatory and Policy Challenges

Regulatory and policy challenges also constrain the widespread adoption of green hydrogen. There is a lack of cohesive global standards and regulations for the production, storage, transportation, and use of green hydrogen. In many regions, existing energy and environmental regulations were designed for conventional energy sources and do not account for the unique properties of hydrogen. This gap in regulation creates uncertainty and can hinder investment in hydrogen infrastructure and projects.

One of the major regulatory hurdles is the classification of hydrogen. In many countries, hydrogen is not explicitly recognized as a distinct energy carrier, which complicates the creation of tailored policies and incentives for its development and deployment. For example, some countries classify hydrogen as a chemical rather than a fuel, limiting its eligibility for renewable energy incentives or clean energy subsidies. Establishing clear definitions and classifications for green hydrogen ensures that it is treated as a legitimate clean energy solution in both domestic and international policy frameworks[53].

In addition to regulatory gaps, there is a need for policies that support the development of hydrogen infrastructure, including electrolyzers, storage facilities, pipelines, and refueling stations. These infrastructure investments often require significant public funding or public-private partnerships, especially in the early stages of hydrogen market development. Governments must provide incentives for private sector investment, such as tax credits, subsidies, and grants, to stimulate innovation and reduce the financial risk associated with hydrogen projects[54].

A key regulatory challenge is the lack of a standardized hydrogen safety and quality framework. Hydrogen is a highly flammable and potentially dangerous substance, and ensuring that hydrogen systems and infrastructure are safe for public use is critical. Regulatory frameworks for the design, construction, and operation of hydrogen facilities must be developed to ensure the safe handling of hydrogen, prevent accidents, and minimize environmental risks. These safety regulations should also address hydrogen storage, transportation, and distribution issues, where specific standards are required to prevent leaks, explosions, or other safety hazards.

Finally, international cooperation is crucial to developing a global hydrogen market. Many countries are pursuing their own hydrogen strategies, but without a common framework for international trade, hydrogen may not achieve its potential as a global energy carrier. Harmonizing regulations across borders, establishing global safety standards, and ensuring consistency in market incentives are critical to successfully scaling hydrogen as an energy resource.

3.4 Grid Integration

Integrating green hydrogen into energy grids presents several challenges related to grid stability, energy storage, and distribution networks. Green hydrogen can act as a versatile storage medium by converting excess renewable energy into hydrogen and then using it to generate power when needed. However, the integration of hydrogen into energy grids requires new infrastructure, advanced control systems, and new operational practices to ensure seamless integration with existing grid systems.

One of the key challenges of grid integration is the coordination of hydrogen production with renewable energy generation. Intermittency in wind and solar power generation can create challenges for balancing supply and demand, and without adequate storage solutions like green hydrogen, this intermittency can result in energy waste or power shortages[55]. Hydrogen can provide a solution to this challenge by allowing for the storage of excess energy during periods of high generation, ensuring that energy is available when renewable production is low. However, integrating hydrogen production with renewable energy generation on a large scale requires advanced forecasting tools, real-time data analytics, and control systems that can effectively manage fluctuating energy production and consumption[4].

Additionally, integrating hydrogen into the grid requires the development of hydrogen-based power generation technologies, such as hydrogen fuel cells or hydrogen combustion turbines. These technologies are still in the early stages of commercialization, and large-scale deployment will require significant investment in research, development, and infrastructure. For example, hydrogen use in power plants requires retrofitting existing gas turbines to accommodate hydrogen as a fuel, which may involve additional costs and technical adjustments.

Another challenge is the capacity of energy transmission and distribution networks to accommodate hydrogen. Most current energy transmission networks are designed for electricity, natural gas, or oil, and may not be able to handle the unique demands of hydrogen. Upgrading these networks to handle hydrogen safely and efficiently requires substantial investment in new infrastructure, including pipelines, compressors, and refueling stations[56]. In addition, hydrogen storage and distribution facilities must be strategically located to ensure that hydrogen is available where and when needed.Finally, the successful integration of green hydrogen into energy grids will require the development of new business models and regulatory frameworks that account for the complexities of hydrogen storage, distribution, and usage. These frameworks must balance the interests of producers, consumers, and regulators while ensuring that hydrogen remains affordable, accessible, and reliable as an energy source[57].

4. OPPORTUNITIES AND SOLUTIONS FOR DECARBONIZING SUPPLY CHAINS

As the global community strives for climate goals and aims to decarbonize various sectors, hybrid renewable energy systems powered by green hydrogen present an array of transformative opportunities. The decarbonization of industrial sectors, efficient energy storage, favorable policy frameworks, market incentives, and technological innovations are all key factors that can drive the widespread adoption of green hydrogen. By focusing on these areas, society can move towards cleaner energy systems, reducing greenhouse gas emissions and mitigating the impacts of climate change.

4.1 Decarbonizing Industrial Sectors

One of the most significant opportunities for green hydrogen is its role in decarbonizing industrial sectors that contribute heavily to global greenhouse gas emissions. These sectors, including heavy industry, transportation, and utilities, are some of the most difficult to decarbonize due to their high energy consumption and reliance on fossil fuels. Hybrid renewable energy systems, especially those that integrate green hydrogen, offer a promising path to reduce emissions from these industries.

- **Heavy Industry**

The industrial sector is responsible for significant global emissions, with industries such as cement, steel, chemicals, and petrochemicals contributing heavily to carbon dioxide (CO_2) emissions. Green hydrogen can play a crucial role in decarbonizing these industries, especially in sectors like steel and cement production, which rely heavily on fossil fuels and emit large quantities of CO_2 in manufacturing[58]. For example, hydrogen can replace coke (a form of carbon) in the steel industry in the blast furnace to produce iron, significantly reducing emissions. This hydrogen-based reduction process, known as direct reduction of iron (DRI), can produce steel without relying on coal, drastically reducing carbon emissions. Similarly, the cement industry, which traditionally relies on limestone and fossil fuels in its production processes, can benefit from green hydrogen by using it as an alternative fuel source in kilns or as part of new carbon capture methods[59].

The adoption of green hydrogen in heavy industries offers the possibility of completely decarbonizing certain high-emission sectors, provided that the costs of hydrogen production decrease and the necessary infrastructure is developed. Additionally, hydrogen can be used as a feedstock in the chemical industry, facilitating the production of ammonia, methanol, and other chemicals more sustainably[60].

- **Transportation**

The transportation sector is another major contributor to global emissions, especially with the widespread use of diesel and gasoline-powered vehicles in freight, aviation, and maritime industries. Green hydrogen offers a compelling solution for decarbonizing this sector, particularly in heavy-duty transport modes that are difficult to electrify, such as long-haul trucking, shipping, and air travel[61].Fuel cell vehicles (FCVs) powered by green hydrogen can provide an alternative to diesel and gasoline engines, offering zero-emissions power for trucks and buses. Hydrogen-powered trucks have already been deployed in pilot projects in various regions, demonstrating the potential of this technology in freight transportation. Similarly, hydrogen can also play a significant role in decarbonizing maritime shipping, where large ships can run on hydrogen fuel cells or use hydrogen to produce synthetic fuels for engines[62].

With its high energy demands and reliance on jet fuel, aviation can also benefit from green hydrogen. Aircraft powered by hydrogen fuel cells or hydrogen-based synthetic fuels could dramatically reduce aviation emissions. While commercial hydrogen-powered aircraft are still in the early stages of development, several companies and research institutions are investing heavily in this technology, with prototypes and test flights expected within the next decade.

- **Utilities and Power Generation**

The utility sector, including power generation, has made significant strides in incorporating renewable energy sources like wind, solar, and hydropower into the energy mix. However, renewable energy systems are intermittent, producing electricity only when the sun shines or the wind blows. This intermittency poses challenges for grid stability and reliability, especially as more renewable energy sources are integrated into power systems.

Green hydrogen can help address this issue by acting as a long-term storage solution. Excess renewable electricity generated during periods of high production (e.g., on sunny or windy days) can be used to produce hydrogen through electrolysis. This hydrogen can then be stored and used as fuel in power plants when renewable energy generation is low, providing a consistent and stable power supply[63]. Hydrogen can be burned in conventional turbines or used in fuel cells to generate electricity, providing a backup source of power and helping to balance supply and demand on the grid.In addition, hydrogen can be used in cogeneration systems, where it serves as both a heat and power source. For example, hydrogen can produce steam for industrial processes while generating electricity in power plants. This type of hybrid renewable energy system can increase energy efficiency and reduce carbon emissions from industrial and power generation sectors[41].

4.2 Green Hydrogen's Role in Energy Storage

One of the most promising applications of green hydrogen lies in its ability to serve as a long-term energy storage solution, effectively addressing one of the most critical challenges in renewable energy deployment—intermittency. The fluctuating nature of renewable energy production, where electricity generation depends on the availability of sunlight or wind, requires efficient storage mechanisms to ensure a stable energy supply[41].

Green hydrogen, produced through water electrolysis using renewable electricity, can store energy in the form of hydrogen gas. Unlike batteries, which store energy in a chemical form, hydrogen can be stored for long periods without significant losses in energy content. This long-term storage capability is crucial for balancing seasonal variations in renewable energy generation. For instance, hydrogen can be stored during periods of surplus renewable energy (such as in the summer months) and used during periods of low renewable energy generation (such as in the winter months), helping to meet peak demand and maintain grid stability[64].

In addition to its ability to store energy for long durations, green hydrogen is easily transportable. Once produced, hydrogen can be stored in underground caverns or tanks and transported over long distances using pipelines, trucks, or ships. This transportability enables hydrogen to be integrated into energy markets on a global scale, providing an efficient and flexible solution for energy storage and distribution.

Moreover, hydrogen storage systems are not limited to large-scale applications. Smaller-scale systems, such as hydrogen storage in homes or businesses, can also be used to provide backup power or support local renewable energy systems. Developing efficient and cost-effective hydrogen storage solutions is key to unlocking the full potential of green hydrogen as a flexible and reliable energy source[65].

4.3 Policy and Market Solutions

The transition to a green hydrogen economy requires supportive policy frameworks and market solutions that incentivize investment in hydrogen technologies and hybrid renewable systems. Governments play a critical role in creating favorable conditions for developing and deploying green hydrogen infrastructure, including subsidies, tax incentives, and grants for research and development.

- **Policy Frameworks**

A robust policy framework is essential to support the growth of the green hydrogen sector. National governments and international organizations need to implement policies that align with the goals of decarbonizing energy systems and reducing greenhouse gas emissions. A key policy priority is the establishment of clear regulatory frameworks for hydrogen production, transportation, storage, and distribution. These regulations should set safety standards, environmental guidelines, and performance metrics for hydrogen systems, ensuring that the development of hydrogen technologies is safe, efficient, and environmentally responsible.

In addition, governments can create market incentives to encourage investment in green hydrogen. This could include direct subsidies for hydrogen producers, tax credits for hydrogen-based technologies, or carbon pricing mechanisms that make fossil fuels less economically attractive. By implementing policies that reduce the cost disparity between green hydrogen and conventional energy sources, governments can encourage private sector participation and accelerate hydrogen infrastructure development.

International cooperation and harmonization of policies will also be crucial in enabling the global hydrogen market. Standardizing regulations, safety protocols, and certification processes for hydrogen will ensure consistency across countries and facilitate cross-border trade in hydrogen. Collaborative efforts between governments, industries, and research institutions will be necessary to foster innovation, improve hydrogen technologies, and create a global hydrogen economy.

- **Market Solutions**

Market-based solutions, such as carbon markets or renewable energy certificates (RECs), can also play a role in promoting the adoption of green hydrogen. Carbon markets provide financial incentives for companies that reduce their carbon emissions, creating a strong economic driver for investing in hydrogen technologies. Similarly, RECs can be used to track the renewable energy content of hydrogen and encourage investment in renewable electricity generation.

In addition, creating a robust hydrogen infrastructure market—comprising hydrogen pipelines, refueling stations, storage facilities, and distribution networks—is essential for ensuring that hydrogen can be produced, stored, and transported efficiently. Public-private partnerships can help finance the development of this infrastructure, enabling the widespread deployment of hydrogen technologies.

4.4 Technological Innovations

Technological innovations are key to improving green hydrogen production, storage, and integration efficiency, scalability, and cost-effectiveness. Several ongoing advancements in hydrogen-related technologies hold the potential to accelerate the adoption of green hydrogen systems.Electrolysis, the process of using electricity to split water molecules into hydrogen and oxygen, is central to green hydrogen production. Significant efforts are underway to improve the efficiency and cost of electrolysis systems. New electrolyzer designs, such as proton exchange membrane (PEM) and alkaline electrolyzers, are optimized to increase energy efficiency and reduce capital costs. Additionally, researchers are exploring advanced materials and coatings that can enhance the performance and longevity of electrolyzers.One promising development is the use of high-temperature electrolysis, which uses heat to assist in the splitting of water molecules. By utilizing heat from renewable sources, such as concentrated solar power or nuclear reactors, high-temperature electrolysis can improve the overall efficiency of hydrogen production, potentially reducing the cost of green hydrogen.

In addition to improvements in electrolysis, technological innovations in hydrogen storage are critical for making hydrogen a viable energy carrier. Advanced storage technologies, such as metal hydride storage systems, liquid organic hydrogen carriers, and cryogenic hydrogen storage, are being developed to provide more efficient and cost-effective solutions for storing and transporting hydrogen.Metal hydride storage systems offer a promising solution by chemically bonding hydrogen to metal alloys, allowing for higher energy density and safer storage. Similarly, liquid organic hydrogen carriers involve storing hydrogen in liquid form by chemically bonding it to organic compounds, which can then be transported and released when needed.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The integration of green hydrogen in hybrid renewable energy systems presents a transformative solution for decarbonizing energy supply chains, addressing the critical challenge of reducing global greenhouse gas emissions. Throughout this discussion, it has been evident that hybrid systems—combining renewable energy sources like solar, wind, and hydro with green hydrogen—have the potential to significantly impact various sectors, including industrial, transportation, and power generation. By utilizing green hydrogen, industries that are difficult to electrify, such as heavy manufacturing and long-haul transportation, can achieve substantial reductions in emissions. Moreover, the ability of green hydrogen to serve as a long-term energy storage solution further enhances its role in stabilizing renewable energy supply, mitigating intermittency issues, and enabling reliable power delivery.

One of the key insights from the research is the crucial role that hybrid systems will play in enabling a sustainable future. The synergy between renewable energy generation and green hydrogen production offers opportunities to tackle energy supply chain inefficiencies, promote energy security, and foster energy independence. Green hydrogen's versatility in serving as a fuel, energy carrier, and storage solution makes it a cornerstone in the transition to a low-carbon economy. As the world faces growing pressures to reduce emissions and achieve net-zero goals, green hydrogen holds immense promise in driving these efforts forward.

However, despite the potential, several technical, economic, and regulatory challenges remain. Technologically, issues related to efficiency, scalability, and the integration of hydrogen with existing infrastructure need to be addressed to make its widespread adoption viable. Additionally, economic barriers, such as the high production and infrastructure development costs, pose obstacles to the deployment of green hydrogen at a large scale. Policymakers also need to create cohesive frameworks and incentives to stimulate investment and innovation in hydrogen technologies. These challenges, though significant, can be mitigated with concerted efforts from governments, industries, and research institutions.

5.2 Future Directions

Several recommendations for future research, technological advancements, and policy developments are essential to overcome the current barriers and unlock the full potential of green hydrogen. First and foremost, the efficiency of green hydrogen production, particularly electrolysis, needs to be improved. Continued research into advanced electrolyzer technologies, such as high-temperature electrolysis, and the development of cheaper, more durable materials for fuel cells are critical to reducing costs and increasing efficiency. Additionally, innovations in hydrogen storage technologies, such as metal hydrides and liquid organic hydrogen carriers, can enhance storage capacity and transportation efficiency, ensuring that hydrogen can be stored for longer periods without energy loss.

From an economic standpoint, reducing the cost of green hydrogen production is paramount. Achieving economies of scale in electrolysis and leveraging low-cost renewable energy sources will drive down the price of green hydrogen, making it more competitive with fossil fuels. Public and private investments in hydrogen infrastructure—such as refueling stations, pipelines, and storage facilities—will further help to facilitate the widespread use of green hydrogen across various sectors.

Governments must play a proactive role in establishing supportive policies and regulatory frameworks that foster the growth of green hydrogen technologies. Creating clear hydrogen production, transportation, and storage standards will ensure safety and promote stakeholder confidence. Additionally, governments can offer incentives, such as subsidies, tax credits, and grants, to encourage research, development, and deployment of green hydrogen solutions. Cross-border collaborations and international agreements on hydrogen standards will also be crucial in ensuring a smooth transition to a global hydrogen economy.

Further research into the integration of hybrid systems—especially hybrid renewable energy grids—will be critical in optimizing the use of green hydrogen. The development of advanced grid management systems that can handle the variability of renewable energy sources and coordinate the production, storage, and consumption of hydrogen will be essential in ensuring the efficient operation of these systems.

REFERENCES

1. S. Chu and A. Majumdar, "Opportunities and challenges for a sustainable energy future," nature, vol. 488, no. 7411, pp. 294-303, 2012.
2. I. Alotaibi, M. A. Abido, M. Khalid, and A. V. Savkin, "A comprehensive review of recent advances in smart grids: A sustainable future with renewable energy resources," Energies, vol. 13, no. 23, p. 6269, 2020.
3. S. E. Hosseini and M. A. Wahid, "Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy," International Journal of Energy Research, vol. 44, no. 6, pp. 4110-4131, 2020.
4. S. G. Nnabuife, A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins, "Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production," International Journal of Hydrogen Energy, 2024.
5. P. Cheekatamarla, "Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors," Energies, vol. 17, no. 4, p. 807, 2024.
6. M.-K. Kazi, F. Eljack, M. M. El-Halwagi, and M. Haouari, "Green hydrogen for industrial sector decarbonization: Costs and impacts on hydrogen economy in qatar," Computers & Chemical Engineering, vol. 145, p. 107144, 2021.
7. U. Y. Qazi, "Future of hydrogen as an alternative fuel for next-generation industrial applications; challenges and expected opportunities," Energies, vol. 15, no. 13, p. 4741, 2022.

8. N. Sazali, "Emerging technologies by hydrogen: A review," International Journal of Hydrogen Energy, vol. 45, no. 38, pp. 18753-18771, 2020.
9. Q. Hassan et al., "Saudi Arabia energy transition: Assessing the future of green hydrogen in climate change mitigation," International Journal of Hydrogen Energy, vol. 55, pp. 124-140, 2024.
10. O. Erdinc and M. Uzunoglu, "Optimum design of hybrid renewable energy systems: Overview of different approaches," Renewable and Sustainable Energy Reviews, vol. 16, no. 3, pp. 1412-1425, 2012.
11. M. A. Basit, S. Dilshad, R. Badar, and S. M. Sami ur Rehman, "Limitations, challenges, and solution approaches in grid-connected renewable energy systems," International Journal of Energy Research, vol. 44, no. 6, pp. 4132-4162, 2020.
12. T. Khan, M. Yu, and M. Waseem, "Review on recent optimization strategies for hybrid renewable energy system with hydrogen technologies: State of the art, trends and future directions," International Journal of Hydrogen Energy, vol. 47, no. 60, pp. 25155-25201, 2022.
13. O. M. Babatunde, J. L. Munda, and Y. Hamam, "A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning," IEEE Access, vol. 8, pp. 75313-75346, 2020.
14. Y. Mohammed, M. Mustafa, and N. Bashir, "Hybrid renewable energy systems for off-grid electric power: Review of substantial issues," Renewable and Sustainable Energy Reviews, vol. 35, pp. 527-539, 2014.
15. M. J. B. Kabeyi and O. A. Olanrewaju, "Sustainable energy transition for renewable and low carbon grid electricity generation and supply," Frontiers in Energy research, vol. 9, p. 743114, 2022.
16. A. H. Ikevuje, J. M. Kwakye, D. E. Ekechukwu, and O. Benjamin, "Optimizing the energy mix: Strategies for reducing energy dependence," Open Access Research Journal of Multidisciplinary Studies, vol. 8, no. 01, pp. 094-104, 2024.
17. M. G. Burns, Managing energy security: an all hazards approach to critical infrastructure. Routledge, 2019.
18. D. R. E. Ewim et al., "Survey of wastewater issues due to oil spills and pollution in the Niger Delta area of Nigeria: a secondary data analysis," Bulletin of the National Research Centre, vol. 47, no. 1, p. 116, 2023.
19. M. Jayachandran et al., "Challenges in achieving sustainable development goal 7: Affordable and clean energy in light of nascent technologies," Sustainable Energy Technologies and Assessments, vol. 53, p. 102692, 2022.
20. Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications," Results in Engineering, p. 101621, 2023.
21. S. Ikemba, K. Song-hyun, T. O. Scott, D. R. Ewim, S. M. Abolarin, and A. A. Fawole, "Analysis of solar energy potentials of five selected south-east cities in nigeria using deep learning algorithms," Sustainable Energy Research, vol. 11, no. 1, p. 2, 2024.
22. Q. Hassan et al., "The renewable energy role in the global energy Transformations," Renewable Energy Focus, vol. 48, p. 100545, 2024.
23. I. Marouani et al., "Integration of renewable-energy-based green hydrogen into the energy future," Processes, vol. 11, no. 9, p. 2685, 2023.
24. B. S. Zainal et al., "Recent advancement and assessment of green hydrogen production technologies," Renewable and Sustainable Energy Reviews, vol. 189, p. 113941, 2024.
25. D. Agrawal, N. Mahajan, S. A. Singh, and I. Sreedhar, "Green hydrogen production pathways for sustainable future with net zero emissions," Fuel, vol. 359, p. 130131, 2024.
26. S. M. Soltani, A. Lahiri, H. Bahzad, P. Clough, M. Gorbounov, and Y. Yan, "Sorption-enhanced steam methane reforming for combined CO2 capture and hydrogen production: a state-of-the-art review," Carbon Capture Science & Technology, vol. 1, p. 100003, 2021.
27. T. Nguyen, Z. Abdin, T. Holm, and W. Mérida, "Grid-connected hydrogen production via large-scale water electrolysis," Energy conversion and management, vol. 200, p. 112108, 2019.
28. M. Rasul, M. Hazrat, M. Sattar, M. Jahirul, and M. Shearer, "The future of hydrogen: Challenges on production, storage and applications," Energy Conversion and Management, vol. 272, p. 116326, 2022.
29. O. Faye, J. Szpunar, and U. Eduok, "A critical review on the current technologies for the generation, storage, and transportation of hydrogen," International Journal of Hydrogen Energy, vol. 47, no. 29, pp. 13771-13802, 2022.
30. F. Qureshi et al., "A State-of-The-Art Review on the Latest trends in Hydrogen production, storage, and transportation techniques," Fuel, vol. 340, p. 127574, 2023.
31. V. Khare, S. Nema, and P. Baredar, "Solar–wind hybrid renewable energy system: A review," Renewable and Sustainable Energy Reviews, vol. 58, pp. 23-33, 2016.

32. P. Denholm, E. Ela, B. Kirby, and M. Milligan, "Role of energy storage with renewable electricity generation," National Renewable Energy Lab.(NREL), Golden, CO (United States), 2010.
33. H. Blanco and A. Faaij, "A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage," Renewable and Sustainable Energy Reviews, vol. 81, pp. 1049-1086, 2018.
34. M. Y. Suberu, M. W. Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," Renewable and Sustainable Energy Reviews, vol. 35, pp. 499-514, 2014.
35. H. J. Undertaking, "Hydrogen roadmap Europe: a sustainable pathway for the European energy transition," 2019.
36. M. Jansen, C. Duffy, T. C. Green, and I. Staffell, "Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea," Advances in Applied Energy, vol. 6, p. 100090, 2022.
37. D. Gielen, E. Taibi, and R. Miranda, "Hydrogen: A Reviewable Energy Perspective: Report prepared for the 2nd Hydrogen Energy Ministerial Meeting in Tokyo, Japan," 2019.
38. S. McQueen et al., "Department of energy hydrogen program plan," US Department of Energy (USDOE), Washington DC (United States), 2020.
39. V. McDonell, K. Chin, R. Flores, and J. Reed, "Hydrogen Based Energy Storage System for Integration with Dispatchable Power Generator (Phase I Feasibility Study)," Univ. of California, Irvine, CA (United States), 2022.
40. E. Taibi, R. Miranda, M. Carmo, and H. Blanco, "Green hydrogen cost reduction," 2020.
41. N. Ma, W. Zhao, W. Wang, X. Li, and H. Zhou, "Large scale of green hydrogen storage: Opportunities and challenges," International Journal of Hydrogen Energy, vol. 50, pp. 379-396, 2024.
42. A. T. Mayyas, M. F. Ruth, B. S. Pivovar, G. Bender, and K. B. Wipke, "Manufacturing cost analysis for proton exchange membrane water electrolyzers," National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2019.
43. Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, "Green hydrogen: A pathway to a sustainable energy future," International Journal of Hydrogen Energy, vol. 50, pp. 310-333, 2024.
44. [44] A. M. Abdalla, S. Hossain, O. B. Nisfindy, A. T. Azad, M. Dawood, and A. K. Azad, "Hydrogen production, storage, transportation and key challenges with applications: A review," Energy conversion and management, vol. 165, pp. 602-627, 2018.
45. S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and perspectives," Renewable and Sustainable Energy Reviews, vol. 50, pp. 457-469, 2015.
46. M. R. Usman, "Hydrogen storage methods: Review and current status," Renewable and Sustainable Energy Reviews, vol. 167, p. 112743, 2022.
47. S. Evro, B. A. Oni, and O. S. Tomomewo, "Carbon neutrality and hydrogen energy systems," International Journal of Hydrogen Energy, vol. 78, pp. 1449-1467, 2024.
48. F. Kourougianni et al., "A comprehensive review of green hydrogen energy systems," Renewable Energy, p. 120911, 2024.
49. S. E. Hosseini and M. A. Wahid, "Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development," Renewable and Sustainable Energy Reviews, vol. 57, pp. 850-866, 2016.
50. A. Odenweller, F. Ueckerdt, G. F. Nemet, M. Jensterle, and G. Luderer, "Probabilistic feasibility space of scaling up green hydrogen supply," Nature Energy, vol. 7, no. 9, pp. 854-865, 2022.
51. M. Bazilian and I. Onyeji, "Fossil fuel subsidy removal and inadequate public power supply: Implications for businesses," Energy Policy, vol. 45, pp. 1-5, 2012.
52. Y.-S. Fu and I.-Y. L. Hsieh, "Evaluating the feasibility and economics of hydrogen storage in large-scale renewable deployment for decarbonization," Energy Strategy Reviews, vol. 55, p. 101545, 2024.
53. F. Dolci et al., "Incentives and legal barriers for power-to-hydrogen pathways: An international snapshot," International Journal of Hydrogen Energy, vol. 44, no. 23, pp. 11394-11401, 2019.
54. R. Bhandari and N. Adhikari, "A comprehensive review on the role of hydrogen in renewable energy systems," International Journal of Hydrogen Energy, vol. 82, pp. 923-951, 2024.
55. M. Khalid, "Smart grids and renewable energy systems: Perspectives and grid integration challenges," Energy Strategy Reviews, vol. 51, p. 101299, 2024.
56. W. Cheng and S. Lee, "How green are the national hydrogen strategies?," Sustainability, vol. 14, no. 3, p. 1930, 2022.
57. B. Lebrouhi, J. Djoupo, B. Lamrani, K. Benabdelaziz, and T. Kousksou, "Global hydrogen development-A technological and geopolitical overview," International Journal of Hydrogen Energy, vol. 47, no. 11, pp. 7016-7048, 2022.

58. E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, "Global strategies and potentials to curb CO2 emissions in cement industry," Journal of cleaner production, vol. 51, pp. 142-161, 2013.
59. B. Rahmatmand et al., "A technical review on coke rate and quality in low-carbon blast furnace ironmaking," Fuel, vol. 336, p. 127077, 2023.
60. W. Liu, H. Zuo, J. Wang, Q. Xue, B. Ren, and F. Yang, "The production and application of hydrogen in steel industry," International Journal of Hydrogen Energy, vol. 46, no. 17, pp. 10548-10569, 2021.
61. O. Bethoux, "Hydrogen fuel cell road vehicles and their infrastructure: An option towards an environmentally friendly energy transition," Energies, vol. 13, no. 22, p. 6132, 2020.
62. O. Fakhreddine, Y. Gharbia, J. F. Derakhshandeh, and A. Amer, "Challenges and solutions of hydrogen fuel cells in transportation systems: a review and prospects," World Electric Vehicle Journal, vol. 14, no. 6, p. 156, 2023.
63. A. H. Schrotenboer, A. A. Veenstra, M. A. uit het Broek, and E. Ursavas, "A Green Hydrogen Energy System: Optimal control strategies for integrated hydrogen storage and power generation with wind energy," Renewable and Sustainable Energy Reviews, vol. 168, p. 112744, 2022.
64. K. Kwon, H.-B. Lee, N. Kim, S. Park, and S. R. Joshua, "Integrated battery and hydrogen energy storage for enhanced grid power savings and green hydrogen utilization," Applied Sciences, vol. 14, no. 17, p. 7631, 2024.
65. S. Kharel and B. Shabani, "Hydrogen as a long-term large-scale energy storage solution to support renewables," Energies, vol. 11, no. 10, p. 2825, 2018.