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Progress in green hydrogen adoption in the African context

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Hydrogen is an abundant element and a flexible energy carrier, offering substantial potential as an environmentally friendly energy source to tackle global energy issues. When used as a fuel, hydrogen generates only water vapor upon combustion or in fuel cells, presenting a means to reduce carbon emissions in various sectors, including transportation, industry, and power generation. Nevertheless, conventional hydrogen production methods often depend on fossil fuels, leading to carbon emissions unless integrated with carbon capture and storage solutions. Conversely, green hydrogen is generated through electrolysis powered by renewable energy sources like solar and wind energy. This production method guarantees zero carbon emissions throughout the hydrogen's lifecycle, positioning it as a critical component of global sustainable energy transitions. In Africa, where there are extensive renewable energy resources such as solar and wind power, green hydrogen is emerging as a viable solution to sustainably address the increasing energy demands. This research explores the influence of policy frameworks, technological innovations, and market forces in promoting green hydrogen adoption across Africa. Despite growing investments and favorable policies, challenges such as high production costs and inadequate infrastructure significantly hinder widespread adoption. To overcome these challenges and speed up the shift towards a sustainable hydrogen economy in Africa, strategic investments and collaborative efforts are essential. By harnessing its renewable energy potential and establishing strong policy frameworks, Africa can not only fulfill its energy requirements but also support global initiatives to mitigate climate change and achieve sustainable development objectives.

KEYWORDS
green hydrogen, renewable energy, energy transition, energy availability, Africa

1 Introduction

Energy is vital for daily life, powering numerous aspects of our existence. Historically, Africa has primarily depended on fossil fuels for its energy needs. However, the prolonged use of fossil fuels has highlighted significant drawbacks, such as the substantial emission of greenhouse gases, as illustrated in Figure 1. These disadvantages have led to a growing imperative to seek alternative energy sources (Ajayi et al., 2016). The urgent need to combat climate change and cut greenhouse gas emissions has driven the global energy sector towards cleaner and more sustainable options. Within this framework, hydrogen, especially green hydrogen produced from renewable energy, has emerged as a viable solution for reducing carbon emissions in various sectors, including industry, transportation, and power generation (Ewing et al., 2020). With its abundant renewable energy resources, Africa is well-positioned to play a crucial role in the global hydrogen economy.

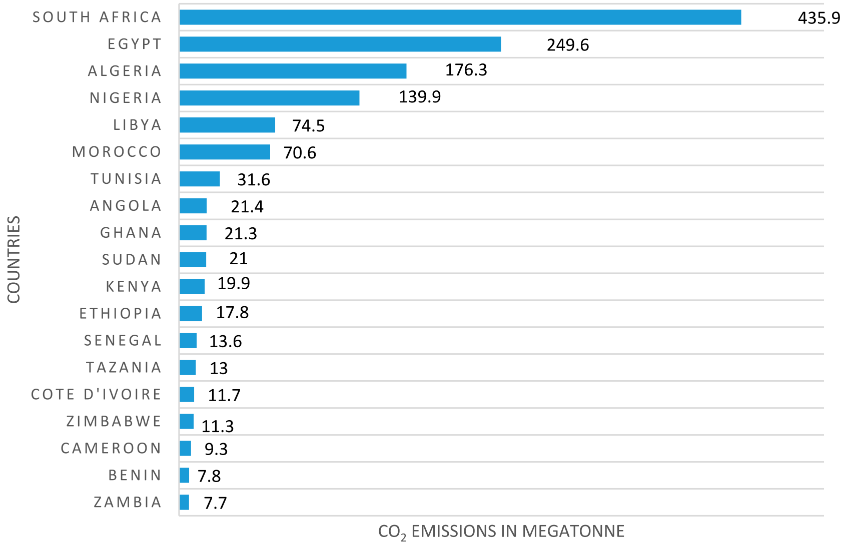

FIGURE 1
Production-based carbon dioxide (CO_2) emissions in Africa in 2021 in mega metric tons (Global Carbon Budget, 2021). https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

1.1 Renewable energy progress in Africa

Africa's renewable energy landscape has seen remarkable advancements over the past decade. Countries across the continent have been harnessing their abundant natural resources which include solar, wind, and hydro in order to build a more sustainable and resilient energy system (Dirisu et al., 2024). According to the International Renewable Energy Agency (IRENA), the installed capacity for renewable energy in Africa grew by over 24% between 2010 and 2020, reaching approximately 56 GW (GW) by the end of 2020 and as at 2023, the total renewable energy capacity in Africa reached about 62 GW as depicted in Figure 2.

- Solar Energy: Africa's solar energy potential is immense, with several regions receiving over 2,000 kWh/m^2 of solar irradiance annually (Ogunniyi and Pienaar, 2019). Countries such as Egypt, Morocco, and South Africa have made significant strides in solar power generation. South Africa had the largest solar energy capacity in Africa as of 2023, reaching over 6 GW (Pourasl et al., 2023). According to the International Energy Agency (IEA, 2023), Egypt recorded the second biggest capacity, at approximately 1.9 GW while Morocco followed with 934 MW of solar energy capacity. The Noor Ouarzazate Solar Complex in Morocco, one of the world's largest concentrated solar power plants, exemplifies the continent's capability in harnessing solar energy (Bakhti, 2024).
- Wind Energy: Wind power is another critical component of Africa's renewable energy mix. Coastal regions and highland areas, particularly in countries like Kenya and South Africa, offer excellent wind resources (Ajayi et al., 2016; Merem et al., 2022). The Lake Turkana Wind Power project in Kenya, the largest wind farm in Africa, has an installed

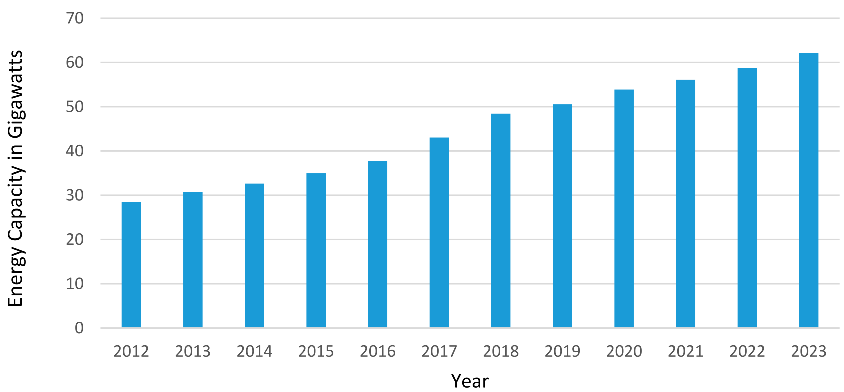

FIGURE 2
Renewable energy capacity in Africa (IRENA, 2024).

capacity of 310 MW (MW) and is a testament to the continent's wind energy potential (Ogeya et al., 2021).

- Hydropower: Hydropower remains the most established renewable energy source in Africa, contributing significantly to the electricity supply in countries like Ethiopia, the Democratic Republic of Congo, Nigeria, and Zambia (Ohunakin et al., 2011; Tiruye et al., 2021). In 2023, 2 GW of hydropower capacity was installed which contributed in increasing the continent's total energy capacity (Bamisile et al., 2023). The Grand Ethiopian Renaissance Dam (GERD), once fully operational, will be Africa's largest hydroelectric power plant, significantly boosting the region's renewable energy capacity (Tiruye et al., 2021).

While the progress in renewable energy adoption in Africa is increasing, the emergence of hydrogen as a viable alternative to fossil fuels can also be adopted to aid the diversification of energy sources in Africa.

1.2 Hydrogen as a viable energy source

Hydrogen is gaining traction as a potential replacement for fossil fuels due to increasing concerns about their environmental and financial drawbacks (Mustafa et al., 2020; Pastore et al., 2022). Bhagwat and Olczak (2020) highlight hydrogen's significant potential in various sectors, such as transportation, power generation, and industrial processes, with global production reaching around 120 million tonnes annually. In contrast, the continuous consumption of fossil fuels releases large amounts of CO_2, exacerbating global warming, and depletes energy resources (Mustafa et al., 2020). Currently, China leads the world in hydrogen production and consumption, using approximately 23.9 million metric tons in 2020. The United States follows, with 11.3 million metric tons of global hydrogen consumption (Kumar et al., 2024).

Hydrogen's appeal lies in its storage capabilities, efficiency, cleanliness, and compatibility with renewable energy sources (Qian et al., 2023). Consequently, hydrogen is crucial in decarbonizing various sectors and mitigating climate change, particularly in transportation and steel manufacturing (Banava, 2023). However, it is important to recognize that while burning hydrogen only emits water vapor, producing it from fossil fuels can still result in CO_2 emissions. To achieve truly emission-free hydrogen production, dependence on renewable energy sources is essential (Stavroulakis et al., 2023). According to Liu et al. (2023), green hydrogen is expected to replace fossil fuels in the near future. Table 1 illustrates the colour classification of hydrogen, the energy sources, and the production methods used.

Hydrogen, the simplest element, consistently yields a carbon-free molecule regardless of its production method (Van Hoecke et al., 2021). However, the methods used to produce hydrogen vary widely, influencing greenhouse gas emissions such as carbon dioxide (CO_2) and methane (CH_4) (Sánchez-Bastardo et al., 2021). Green hydrogen, produced from renewable sources like wind, solar, and hydropower, is viewed as a clean alternative to fossil-derived hydrogen (Kakoulaki et al., 2021). Its production represents a significant step toward achieving a carbon-neutral future, with applications spanning transportation, power generation, and industrial sectors (Kovač et al., 2021).

The process of electrolysis can be represented by the chemical equation:

$$2H_2O + \text{electricity} \rightarrow 2H_2 + O_2$$

Electrolytic hydrogen generation ensures purity levels exceeding 99.95%, free from hydrocarbon contamination (Burton et al., 2021; Newborough and Cooley, 2020). Electrolytic hydrogen production, unless powered by electricity from fossil fuel stations, is not associated with CO_2 or methane emissions, thereby obviating the necessity for carbon capture and storage.

The growing demand for hydrogen across sectors such as transportation, power generation, and manufacturing underscores the urgency of producing hydrogen from renewable energy sources (Ahmed et al., 2023). The potential for green hydrogen to decarbonize hard to abate sectors like heavy industry such as cement production, steel manufacturing, and chemical processing, and shipping and aviation has made it a crucial component of the energy transition (Harichandan et al., 2023) however, several factors need to be considered when producing green hydrogen using renewable energy sources.

TABLE 1 Showing the colour scheme of hydrogen (Ajanovic et al., 2022; Khan and Al-Ghamdi, 2023).

Source	Method of production	Colour
Renewable Energy	Water electrolysis using electricity generated from renewable energy sources	Green Hydrogen
Fossil fuels	Partial oxidation causing CO emissions in the process	Grey Hydrogen
Natural gas	Natural gas reforming	Grey Hydrogen
Methane	Pyrolysis where the by-product is solid carbon	Torquoise Hydrogen
Mixed grid electricity	Water electrolysis using grid electricity	Yellow Hydrogen
Nuclear Energy	Water electrolysis using electricity from Nuclear power plants	Pink Hydrogen
Black Coal	Gasification	Black Hydrogen
Lignite	Gasification	Brown Hydrogen

1.3 Factors considered when producing green hydrogen

Green hydrogen production hinges fundamentally on several key factors, each crucial for its economic viability, environmental sustainability, and widespread adoption as a clean energy solution.

1.3.1 Renewable energy availability

The production of green hydrogen is fundamentally anchored on the disposal and accessibility of renewable energy sources (Sarker et al., 2023). These sources, primarily solar, wind, and hydroelectric power, are pivotal in the electrolysis process that splits water into hydrogen and oxygen, producing green hydrogen. Regions endowed with a consistent and substantial supply of these renewable resources are naturally poised to become leaders in green hydrogen production, capitalizing on their sustainability and reduced environmental footprint compared to fossil fuel-based methods (Osman et al., 2023). As at 2018 however, Renewable energy sources was the least used in hydrogen production globally as depicted in Figure 3.

The variability and intermittency inherent in renewable energy sources present unique challenges to green hydrogen production (Coban et al., 2023). Fluctuations in solar irradiation, wind speeds, or water flow rates can impact the efficiency and reliability of electrolysis processes (Kojima et al., 2023). As such, integrating advanced energy storage systems and smart grid technologies becomes imperative. These systems can store excess energy during peak production periods and release it during low or no production periods, ensuring a continuous and reliable energy supply for hydrogen production.

While some regions may have abundant solar resources, they may lack sufficient wind or hydroelectric power. This disparity necessitates a multifaceted approach to green hydrogen production, incorporating a mix of renewable energy sources to optimize production efficiency and reliability. Strategic planning and investment in interconnected energy grids and cross-regional energy trading can facilitate the seamless integration and distribution of diverse renewable energy sources, bolstering the feasibility and scalability of green hydrogen production initiatives (Okolie et al., 2021; Raman et al., 2022).

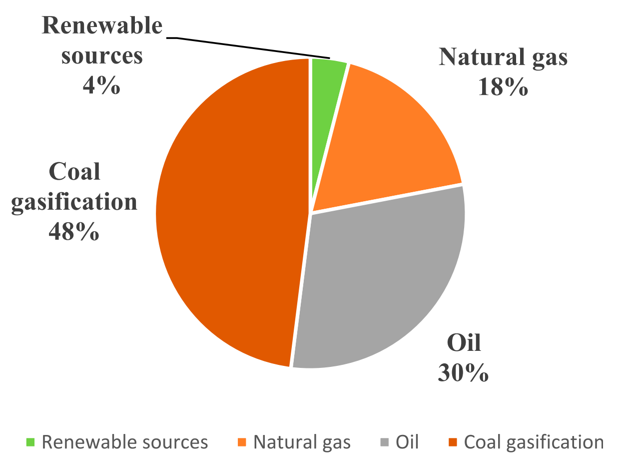

FIGURE 3
Global Hydrogen production by main source in 2018 (IRENA, 2018; Patonia and Poudineh, 2022).

1.3.2 Electrolysis efficiency

According to Hassan et al. (2023a), Electrolysis efficiency stands as a pivotal factor influencing the economic viability and scalability of green hydrogen production. Electrolysis is the process through which water is split into hydrogen and oxygen using an electric current. The efficiency of this process determines the amount of electrical energy required to produce a given quantity of hydrogen, directly impacting production costs and overall competitiveness of green hydrogen against conventional hydrogen production methods (Orjuela-Abril. et al., 2023).

Advancements in electrolysis technology have led to improvements in efficiency and reduced energy consumption over recent years. Traditional alkaline electrolysis, although mature and well-established, typically exhibits lower efficiency rates compared to proton exchange membrane (PEM) and solid oxide electrolysis technologies (Li and Baek, 2021). PEM electrolysis according to Zhang et al. (2022) has garnered significant attention due to its higher efficiency, rapid response times, and scalability, making it particularly suitable for decentralized green hydrogen production applications. However, PEM is also associated with high costs and the need for rare and expensive materials (Wappler et al., 2022). Table 2 shows the characteristics of Alkaline, PEM and Solid Oxide (SOE) Electrolysers.

Factors influencing electrolysis efficiency extend beyond technological advancements to include operational parameters and system design (Agyekum et al., 2022). Optimizing operating conditions, such as electrolyte concentration, temperature, and pressure, can significantly enhance electrolysis efficiency. Additionally, the integration of renewable energy sources with electrolysis systems, leveraging peak renewable energy production periods, can further improve overall system efficiency and reduce energy costs.

Moreover, according to Jiao et al. (2021), electrolysis efficiency is intrinsically linked to the quality and purity of the produced hydrogen. High-efficiency electrolysis processes typically yield hydrogen with lower impurity levels, meeting stringent quality requirements for various applications, from fuel cells to industrial processes. As such, continuous research and development efforts are focused on enhancing electrolysis efficiency, reducing energy consumption, and improving hydrogen purity to drive down production costs and enhance the competitiveness of green hydrogen.

1.3.3 Scale of production

The gauge of production is another significant factor to consider as it is crucial in the deployment and widespread adoption of green hydrogen technologies (Li et al., 2023). As with many industrial processes, economies of scale can significantly influence the cost-effectiveness and commercial viability of green hydrogen production. Large-scale production facilities can benefit from bulk purchasing, streamlined operations, and optimized supply chains, leading to reduced production costs per unit of hydrogen (Lagioia et al., 2023). The hydrogen production landscape has been dominated by large centralized production facilities, leveraging economies of scale to produce hydrogen from fossil fuel-based feedstocks (Jiao et al., 2021). However, the transition to green

TABLE 2 Characteristics of Different types of electrolyser technologies (Conte et al., 2009).

	Alkaline	PEM	SOE
Electrolyte	Aqueous potassium hydroxide	PFSA membranes (e.g., Nafion)	Yttria Stabilises Zirconia (YSZ)
Cathode	Nickel, Nickel-Molybdenum alloy	Platinum-Palladium alloy	Nickel/YSZ
Anode	Nickel-Cobalt alloys	Ruthenium oxide	YSZ
Operating Temperature (^{O}C)	60–80	50–80	500–850
Operating Pressure (Bar)	30	70	1–25
Stack Lifetimes	60–100 k	20–60 k	Less than 10 k
Technology Readiness	Matured	Commercialised	Demonstration
Efficiency (%)	50–70	60–80	80–95

hydrogen necessitates a shift towards decentralized and distributed production models, leveraging renewable energy sources and modular electrolysis systems. These smaller-scale production facilities can be strategically located closer to renewable energy generation sites, reducing transmission losses and infrastructure costs while enhancing system efficiency (Osman et al., 2023).

The cost of hydrogen production varies significantly depending on the type of hydrogen, production technique, and the source of electricity (Ishaq et al., 2022). Grey hydrogen, produced from natural gas through steam methane reforming, is currently the cheapest option but is associated with high carbon emissions. Blue hydrogen, which incorporates carbon capture and storage (CCS) with steam methane reforming, has a higher cost due to the additional CCS processes but results in lower emissions (Oni et al., 2022). Green hydrogen, produced via electrolysis using renewable electricity, is the most environmentally friendly option but is also the most expensive. The cost of green hydrogen is heavily influenced by the price of renewable electricity and the efficiency of the electrolysis process. PEM electrolysis, for example, offers higher efficiency and rapid response times but comes with higher costs due to the need for rare and expensive materials (Zhang et al., 2022). Alkaline electrolysis is generally cheaper but less efficient and slower in response (Santos et al., 2021).

Ultimately, the choice of production technique and the type of hydrogen produced will depend on the specific economic and environmental priorities, as well as the availability of renewable energy sources. The push towards decentralized production models aims to optimize these factors by situating hydrogen production closer to renewable energy generation, thereby minimizing costs and maximizing system efficiency. Advancements in electrolysis technology and the decreasing costs of renewable energy sources, such as solar and wind power, are facilitating the development of larger-scale green hydrogen production facilities. The integration of renewable energy with electrolysis systems at scale can result in significant reductions in greenhouse gas emissions and enhance the overall sustainability credentials of green hydrogen (Zhang et al., 2022).

1.3.4 Infrastructure and logistics

The infrastructure and logistics required for producing and distributing green hydrogen are also important factors to consider according to Kumar et al. (2023). This includes the availability of water and renewable energy sources, as well as the transportation and storage of hydrogen. Various hydrogen storage techniques play a crucial role in this process, ensuring that hydrogen can be efficiently stored and readily available when needed (Liu et al., 2023). They include:

- Compressed Gas Storage: This is the most common method, where hydrogen is stored under high pressure in specially designed tanks. Compressed gas storage is relatively straightforward and widely used, especially in the transportation sector. However, it requires robust and heavy containers to withstand high pressures, which can impact efficiency and cost (Orlova et al., 2023).
- Liquid Hydrogen Storage: In this method, hydrogen is cooled to cryogenic temperatures (−253°C) and stored as a liquid. Liquid hydrogen has a higher energy density compared to compressed gas, allowing for more hydrogen to be stored in a given volume. However, the liquefaction process is energy-intensive and requires significant cooling infrastructure, making it costly (Aziz, 2021).
- Metal Hydride Storage: Hydrogen can be stored in metal hydrides, which are compounds formed by the reaction of hydrogen with metals or alloys. Metal hydride storage systems have high energy densities and can operate at lower pressures compared to compressed gas storage. However, they are often heavy and can be expensive due to the materials used (Klopčič et al., 2023).
- Chemical Storage: Hydrogen can be stored in chemical compounds such as ammonia, formic acid, or liquid organic hydrogen carriers (LOHCs). These chemicals can release hydrogen upon demand through chemical reactions. Chemical storage offers the advantage of high energy density and ease of transport but requires additional processes to release the stored hydrogen, which can impact efficiency (Carmo and Stolten, 2022).
- Underground Storage: Large-scale storage of hydrogen can be achieved in underground geological formations such as salt caverns, depleted oil and gas fields, or aquifers. Underground storage can handle large quantities of hydrogen and is suitable for long-term storage. However, it requires suitable geological conditions and significant infrastructure investments (Tarkowski and Uliasz-Misiak, 2022).

Developing an efficient and cost-effective infrastructure for the production and distribution of green hydrogen is critical to the success of the technology (Morlanés et al., 2021).

Countries that have launched National initiatives to promote the deployment of green hydrogen across different sectors include Germany, Japan, South Korea and others. In Europe, the European Union recently launched Hydrogen strategy aim to establish a hydrogen economy that is competitive, sustainable and able to drive long-term economic growth (Khan and Al-Ghamdi, 2023).

The estimation of the green hydrogen (H_2) production potential represents the initial stage on the road to integrating the Hydrogen Economy into the energy systems of a country or region (Posso et al., 2023). Fuel cells and other hydrogen-based technologies are increasingly seen as a key pillar of global decarbonization efforts (Lindner, 2023).

Once hydrogen is generated and stored for future use, the focus shifts to methods of converting it into energy. The primary approach involves using hydrogen in fuel cells, which are electrochemical devices that convert chemical energy directly into electrical energy (Rai et al., 2022). Unlike batteries and other energy storage systems that rely on stored energy, fuel cells can continuously supply electricity as long as fuel is provided, offering uninterrupted power (Felseghi et al., 2019).

The cost-effectiveness of hydrogen production through electrolysis primarily hinges on the cost of electricity used in the process and the efficiency of electrolyzers (Martinez de Leon et al., 2023). This underscores the importance of optimizing electrolysis processes to enhance the economic viability of hydrogen as an energy carrier.

2 Applications of green hydrogen

One major advantage of green hydrogen is its environmental cleanliness. Unlike other types of hydrogen, green hydrogen is produced using renewable energy sources, resulting in zero carbon emissions. It can be used in a wide range of applications across various industries, including transportation, power generation, and industrial processes, offering a sustainable and carbon-free alternative.

2.1 Transportation

According to Pasini et al. (2023), green hydrogen can be used for transportation and is considered as one of the most promising options for decarbonizing the different modes of transportation, including cars, buses, trucks, trains, and airplanes as depicted in Figure 4.

Green hydrogen can be used as a fuel for hydrogen fuel cell vehicles. These vehicles use a fuel cell to convert hydrogen into electricity, which then powers an electric motor (Inci et al., 2021). The only emission from a hydrogen fuel cell vehicle is water vapor, making it a zero-emission vehicle. The use of green hydrogen as a fuel for transportation can help to reduce greenhouse gas emissions and improve air quality (Vardhan et al., 2022).

Green hydrogen may also be used as a fuel for waterborne transport, such as ships and boats (Jie et al., 2023). Hydrogen fuel cell vessels are becoming increasingly popular, especially for ferries and small inland waterway ships (Chatelier, 2023).

2.2 Power generation

Green hydrogen can also be used to generate electricity in fuel cells or through combustion in a gas turbine (Hwang et al., 2023). Green hydrogen can be used as a fuel in fuel cells, which convert the chemical energy of hydrogen and oxygen into electrical energy, water and heat (Liu et al., 2023). Fuel cells are highly efficient and emit only water vapour, making them a sustainable alternative to traditional fossil fuel power plants (Azni et al., 2023).

This can be particularly useful in remote locations or off-grid settings, where traditional power sources may not be available. The use of green hydrogen for power generation can help to reduce greenhouse gas emissions and improve energy security. Green hydrogen can be used in fuel cells (an electrochemical device that converts the chemical energy of green hydrogen and oxygen into electricity) to produce electricity (Yu et al., 2023). Fuel cells have high efficiency and emit only water and heat as byproducts.

Green hydrogen can also be burned in combustion engines to generate electricity (Teoh et al., 2023), similar to burning natural gas, except that the only emission is water vapor. It can also be used in specially designed gas turbines to generate electricity (Hassan et al., 2023a). However, it is important to note that green hydrogen, like other forms of hydrogen, cannot be used in conventional gas turbines without modifications (Bothien et al., 2019). The development of specific turbines capable of efficiently burning hydrogen is an area of active research. Additionally, natural gas-hydrogen blends can be used for electricity generation via modified gas turbines, providing a transitional solution towards cleaner energy. Similarly, green ammonia produced from hydrogen can also be used for electricity generation in gas turbines, offering another pathway to leverage hydrogen for sustainable energy production (Ağbulut et al., 2023).

2.3 Industrial processes

Green hydrogen can also be used in a variety of industrial processes, such as refining, chemical production, and steel production (Genovese et al., 2023). The global transition to climate neutrality will necessitate not only renewable power but also climate-neutral energy carriers such as hydrogen and its derivatives (Runge et al., 2023). These processes typically require large amounts of energy and produce significant greenhouse gas emissions. The use of green hydrogen as a feedstock or fuel for these processes can help to reduce greenhouse gas emissions and improve the sustainability of these industries.

Considering the factors that need to be considered when producing green hydrogen from renewable energy sources, this paper will be able to determine the prospects for the development of green hydrogen in Africa as a continent and also identify the various challenges that may be able to further delay or even hinder the development of green hydrogen in Africa.

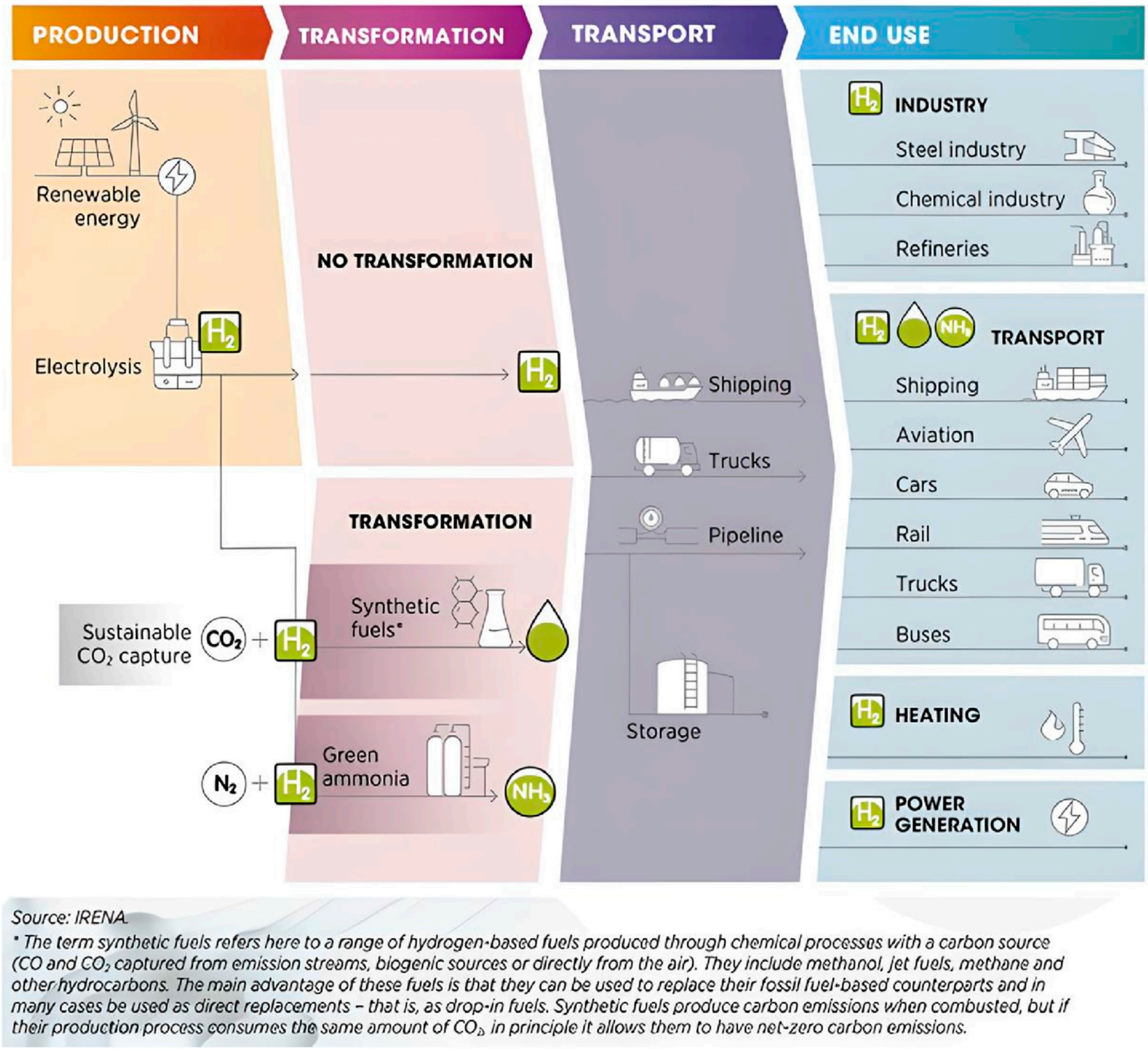

FIGURE 4
Process of Green hydrogen production to application (IRENA, 2020; Pachencko et al., 2023).

3 Prospects for the adoption of green hydrogen for africa

Africa has the potential to become a significant producer and exporter of green hydrogen due to its extensive renewable energy supplies (Panchenko et al., 2023). Green hydrogen adoption prospects in Africa are highly promising, and there are various elements that make this a potentially appealing alternative for the continent some of which are stated below.

3.1 Abundant renewable energy resources

As mentioned earlier, Africa has some of the world's largest renewable energy resources. Africa has not fully tapped into its abundant renewable energy potential. Estimates indicate that the continent's total renewable energy resources far exceed current and future energy requirements (Sohani et al., 2023). This underscores the immense opportunity for Africa to harness renewable sources to meet its energy demands sustainably and contribute significantly to global renewable energy goals. The continent has vast solar, wind, and hydropower potential, which make it an ideal location for the production of green hydrogen. With an abundance of renewable energy sources, African countries can produce green hydrogen in a sustainable and environmentally friendly way.

The continent is blessed with vast areas of land and water bodies that receive huge amounts of solar radiation, wind and hydrological resources. Solar energy is especially abundant in Africa, with large areas of the continent receiving high levels of sunlight throughout the year. Wind energy is also abundant in many parts of Africa, especially along the coasts and in high altitude areas. These resources could provide Africa with more energy than it could ever need and pave the way for the continent to become self-sufficient, environmentally sustainable, and economically prosperous.

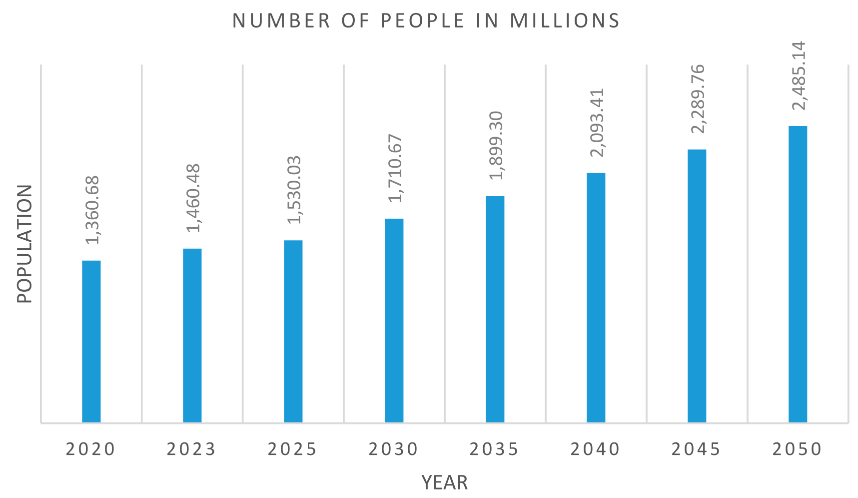

FIGURE 5
Forecast of the total population of Africa from 2020 to 2050 (Statista, 2024).

3.2 Growing demand for energy

According to global demographics, Africa's population was projected to grow by 2.37 percent in 2022 compared to the previous year. Since 2000, the continent has consistently experienced population growth rates exceeding 2.45 percent, reaching a peak of 2.59 percent between 2012 and 2013. Despite a slight slowdown in recent years, Africa's population is expected to continue increasing significantly in the foreseeable future, as illustrated in Figure 5 (Saifaddin Galal, 2023).

This demand is likely to rise more in the future years, and green hydrogen can assist supply it in a sustainable manner. Due to this demand, there is increasing international support and investment in green hydrogen development in Africa. The European Union, for instance, has identified Africa as a key partner for its green hydrogen strategy and has committed to supporting the adoption and development of green hydrogen in the continent (Sadik-Zada, 2021). Other countries, such as Japan and Australia, have also expressed interest in investing in green hydrogen projects in Africa (Kar et al., 2023).

3.3 Potential for export

Africa has the potential to become a significant producer and exporter of green hydrogen due to its extensive renewable energy supplies (Razi, Faran et al., 2022). With a growing emphasis on decarbonization and the need to transition towards clean and sustainable energy sources, green hydrogen presents a significant opportunity for African nations to drive economic growth while addressing environmental challenges.

According to Agyekum (2024), Africa's strategic geographic location offers access to key global markets, positioning the continent as a crucial player in the emerging hydrogen economy. With proximity to Europe, Asia, and the Middle East, African nations have the opportunity to export green hydrogen to regions seeking to reduce their carbon footprint and meet their renewable energy targets. This not only drives economic growth and job creation but also strengthens Africa's position as a reliable supplier of clean energy to the world.

Furthermore, Africa's dedication to sustainable development and climate action strengthens its potential for exporting green hydrogen (Bouchene et al., 2021). Embracing clean energy technologies and reducing reliance on fossil fuels enables African nations to lead in mitigating climate change and promoting environmental stewardship. Exporting green hydrogen not only supports global efforts towards achieving net-zero emissions but also unlocks new economic opportunities and fosters inclusive growth throughout the continent (Nwokolo et al., 2023). This dual benefit of environmental leadership and economic advancement positions Africa strategically in the global energy transition.

4 Advantages of green hydrogen adoption in African countries

Green hydrogen development and adoption in Africa has its benefits to the people, the continent and even the world at large. The adoption of Green hydrogen in African countries can also aid in the transition from polluted energy sources to clean and renewable energy sources.

4.1 Energy security

The potential for solar and wind energy in Africa is very high, with the region having some of the best solar and wind resources globally. According to IRENA (2020), Africa receives about 325 days of bright sunshine annually in many regions, particularly in North Africa and the Sahel region. This high solar irradiance makes these areas ideal for solar energy development (Chun et al., 2022). Additionally, IRENA reports that Africa has an estimated wind energy potential of over 1800 GW, particularly along coastal regions and in high-altitude areas such as the Ethiopian Highlands. The production of green hydrogen using these renewable resources can contribute towards energy security for Africa, particularly in remote areas where grid infrastructure is not readily available (Bhandari, 2022). The development of green hydrogen can provide energy security to African countries in several ways.

By developing the capacity for green hydrogen production, these countries can diversify their energy sources and reduce their dependence on fossil fuels (Szemat-Vielma et al., 2023). This can make them less subject to price fluctuations in fossil fuels for their energy demands. Green hydrogen production, on the other hand, can diversify their energy mix by using renewable energy sources such as solar, wind, and hydro power. This can drastically reduce their reliance on fossil fuels, which are volatile in price and vulnerable to supply disruptions. With a more diversified energy mix, African countries can enhance their energy security and increase their resilience to external shocks (Chu, 2023).

Also, most African countries are net energy importers, which makes them vulnerable to fluctuations in global oil and gas prices (Galimova et al., 2023). Developing their own green hydrogen production capabilities can help them become more energy independent and reduce their dependence on imported fuel (Müller et al., 2023). This can ensure a consistent and predictable energy supply, improve their balance of payments, and improve their overall energy security.

4.2 Economic growth and employment opportunities

The adoption of green hydrogen in Africa can accelerate economic growth and create employment opportunities (Bhagwat and Olczak, 2020). The establishment of the green hydrogen industry can create job opportunities from manufacturing, installation, and maintenance of green hydrogen facilities to the production of green hydrogen fuel cells. The sector can also provide an opportunity for African countries to diversify their economies and reduce their reliance on fossil fuels.

The development of green hydrogen technology can generate economic growth in African countries by creating new job opportunities, developing local industries, and attracting foreign investments. Countries such as Morocco, Egypt, and South Africa have already started investing in this technology (Agyekum et al., 2023), and this could significantly reduce their dependence on fossil fuels and strengthen their energy security.

Green hydrogen production can support sustainable development in African countries by providing a clean and renewable source of energy. The development of a green hydrogen economy can also lead to the creation of new job possibilities, the expansion of local economies, and the development of new industries.

4.3 Reduction of greenhouse gas emissions and dependence on fossil fuels

Green hydrogen offers substantial benefits for Africa, including the potential to reduce global and local greenhouse gas emissions (Li et al., 2023). In Africa, where fossil fuels dominate the energy landscape and contribute significantly to greenhouse gas emissions, green hydrogen can serve as a cleaner alternative in sectors like transportation, power generation, and industry, fostering a more sustainable future. By generating green hydrogen from renewable sources, African countries can advance sustainable development goals, improving air quality and promoting environmental sustainability.

Adopting green hydrogen also holds promise for reducing Africa's reliance on imported fossil fuels, which exposes the region to volatility in global oil prices and supply disruptions (Odoom et al., 2023). Instead, green hydrogen production offers a stable and locally sourced energy option, enhancing energy security across the continent. Furthermore, embracing green hydrogen technology presents Africa with an opportunity to lead the global transition to renewable energy, a role that has often been overlooked in past energy revolutions (Panchencko et al., 2023).

The adoption of green hydrogen stands to benefit Africa through enhanced energy security, job creation, reduced dependence on imported fossil fuels, and leadership in renewable energy innovation. It is crucial for African governments and stakeholders to prioritize the development of green hydrogen infrastructure, supported by robust policies and regulations that facilitate its widespread adoption across the region.

5 Challenges in the development and adoption of green hydrogen

While the prospects for green hydrogen development in Africa are quite promising, there are several challenges that will need to be addressed in order to make it a viable option for the continent. Lack of infrastructure, high cost of production and limited technical expertise are challenges in the development of green hydrogen.

5.1 Lack of infrastructure

Developing green hydrogen in Africa faces significant challenges, primarily due to inadequate infrastructure (Sadik-Zada, 2021). The production, storage, and transportation of green hydrogen necessitate substantial investments in facilities such as production plants, pipelines, storage tanks, and refueling stations (Schaffert, 2022; Hassan et al., 2023b). Without proper infrastructure, the cost and feasibility of generating and distributing hydrogen could become prohibitively high (Azadnia et al., 2023).

Moreover, the lack of infrastructure poses a barrier to the adoption of hydrogen fuel cell vehicles, as the availability of refueling stations is crucial for their practical use (Geçici et al., 2023; Latapi et al., 2023). This limited accessibility may deter potential consumers from embracing hydrogen technology. Furthermore, insufficient infrastructure could restrict access to the renewable energy sources required for green hydrogen production (Nemmour et al., 2023). In regions lacking adequate renewable energy capacity, the potential for producing green hydrogen may be constrained, hindering the development of a hydrogen-based economy (Khan and Al-Ghamdi, 2023).

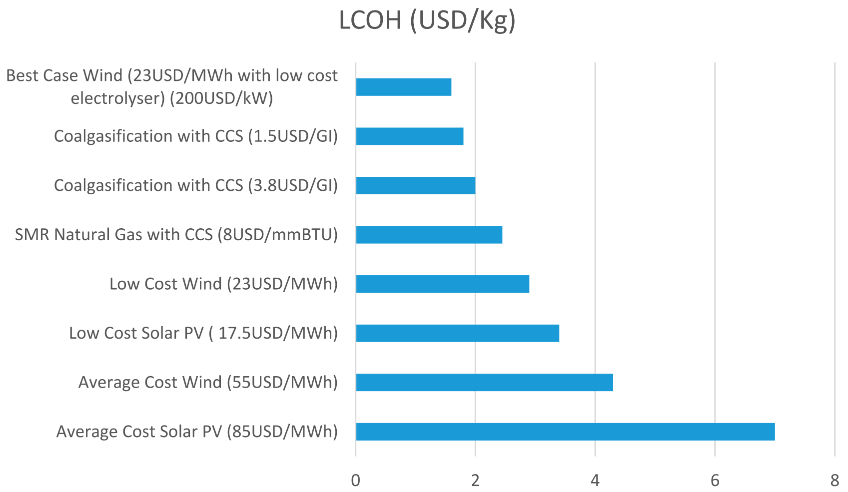

FIGURE 6
Hydrogen production cost by renewable and non-renewable energies in 2019 (IRENA, 2020).

Overall, the expansion and widespread adoption of green hydrogen as a sustainable energy solution in Africa hinge significantly on substantial investments in infrastructure. Addressing these infrastructure gaps is crucial to unlocking the full potential of green hydrogen in the region.

5.2 High costs of production

Developing green hydrogen in Africa faces a significant hurdle due to its high production costs (Sontakke, Ujwal, and Santosh Jaju, 2021). While the costs of renewable energy technologies have decreased recently, producing green hydrogen remains more expensive than traditional fossil fuels as shown in Figure 6 (Dong et al., 2022). Green hydrogen production involves electrolyzing water using renewable energy sources like wind and solar power, which adds to its cost compared to hydrogen derived from fossil fuels (Schnuelle et al., 2022).

This higher production cost poses several challenges for green hydrogen development. Firstly, it limits the competitiveness of green hydrogen against cheaper energy sources such as natural gas or gasoline (Kendall Kelvin, 2022). Without substantial government subsidies or incentives, green hydrogen may struggle to penetrate the market (Kar et al., 2023). Despite efforts to reduce electrolyzer technology costs since 2020 (Newborough and Cooley, 2020), the costs remain relatively high. For African countries, which often have limited financial resources, the high cost of green hydrogen production further complicates investment in its development. Addressing these cost barriers is crucial to making green hydrogen a viable and widespread energy solution in the region.

Secondly, the high cost of production could limit the availability of green hydrogen (Terlouw, et al., 2022). If the cost of creating green hydrogen is too high, it may be difficult to scale up production to meet demand, limiting the technology's potential for widespread adoption. Even with the current subsidy removal which has rapidly increased the price of diesel, gasoline, kerosene and other fuels in Nigeria, the most populated country in Africa, the cost of the conventional fuels will still not match up to that of the production and development of green hydrogen.

The high cost of production could also slow down innovation and research in green hydrogen development (Jilani et al., 2023). If the cost of manufacturing green hydrogen is too expensive, it may be more difficult to invest in more research and development to enhance efficiency and lower the cost of the technology. The average price of producing hydrogen by solar PV and wind energy is much higher than that of fossil fuel, while the decrease in the price of solar PV and wind energy is considered competitive. The International Renewable Energy Agency (IRENA) is expecting that the cost of hydrogen production via renewable energies will fall and become even cheaper than fossil fuel in 2050 (International Renewable Energy Agency, 2020)

5.3 Limited technical/qualified expertise

Developing green hydrogen requires technical expertise in areas such as renewable energy, chemistry, and engineering. Africa as a continent has a lot of academic potential but many African countries have limited qualified expertise to develop and maintain green hydrogen infrastructure (Mneimneh et al., 2023), while some of the personnel that may have the skills and are qualified to develop and maintain green hydrogen infrastructure end up migrating to other countries due to the high rate of unemployment (Rufus et al., 2022). The select few that remain may end up becoming entrepreneurs and having their own personal businesses which may be different from their area of specialization because of the need to generate funds for personal use. This can make it difficult to design and operate green hydrogen production facilities, as well as maintain and repair them over time (Mali et al., 2021).

It will be challenging to develop new procedures and technologies for manufacturing green hydrogen without technical competence. This may limit the ability of the required technical expertise, and the development of green hydrogen technology may be slowed or hampered by concerns about safety, efficiency, and cost-effectiveness.

Green hydrogen production from renewable sources such as solar and wind, for example, necessitates extensive knowledge of electrolysis technology and the materials used in electrolysis cells. There is a danger of errors in the design and execution of the electrolysis process if technical expertise is absent or lacking, which could result in decreased efficiency or even safety issues.

Furthermore, technical skill is required for the transportation and storage of hydrogen (Sun et al., 2023). Hydrogen is a highly combustible gas that must be handled with care to ensure safe transit and storage (Tang Dan et al., 2023). Also, the storage of hydrogen necessitates sophisticated and advanced knowledge of materials science in order to design efficient and cost-effective storage solutions (Singh et al., 2023).

5.4 Policy and regulatory framework

The lack of clear policy and regulatory frameworks is another challenge facing green hydrogen development in Africa (Ballo et al., 2022). In many cases, there is a lack of clarity around the legal and regulatory frameworks that govern the production, distribution, and use of green hydrogen (Chege, 2023; Gordon et al., 2023). This can generate uncertainty for investors and make it difficult to obtain the necessary funds to promote green hydrogen development in developing countries. (Hassan et al., 2023b).

5.5 Competing priorities

Although electrolyser technology is currently being upscaled and cost-reduced in preparation for volume production (Kampouta, 2022), some African countries would still be unable to make it a top priority because it is still very expensive. For example, according to Gigastack phase 1 report 1, 2020, the price of a 100 MW PEM electrolyser system from ITM Power is expected to fall to $530 per kW by 2024, but many African countries may not still be able to concentrate on this as they have other competing priorities which would also involve a large amount of investment and financial assistance (Gigastack, 2020). These African countries face competing priorities and basic needs, such as addressing poverty and improving access to healthcare and education (Ayoo, 2022). These priorities can make it even more difficult to prioritize investment in green hydrogen development, which may be viewed as a longer-term priority in comparison to other more pressing demands.

Also, some governments and businesses may prioritize renewable energy sources like wind and solar power over green hydrogen (Munim et al., 2023), while others may prioritize energy storage technologies like batteries. Competing priorities might be a big obstacle for green hydrogen development. It is possible however to find areas of common ground and work toward a shared vision for the development of a sustainable hydrogen economy through good communication and collaboration among stakeholders.

5.6 Research development and innovation

Research, development, and innovation (RDI) are pivotal in advancing green hydrogen technologies, addressing technical challenges, and enhancing competitiveness in the energy sector. Efforts in RDI focus on several critical areas to accelerate the adoption and scale-up of green hydrogen (Heilala et al., 2022).

In electrolysis efficiency, ongoing research aims to improve the performance of electrolyzers, which convert water into hydrogen and oxygen using electricity. Innovations in materials and catalysts are crucial for enhancing electrolyzer efficiency and durability, reducing energy consumption, and lowering production costs (Burton et al., 2021). Additionally, advancements in storage and transportation technologies are essential. Researchers are exploring novel storage materials and infrastructure solutions to safely and efficiently store and transport hydrogen, ensuring its availability as a reliable energy carrier (Ahmad et al., 2021). Integrating green hydrogen production with renewable energy sources, such as solar and wind power, is another key area. Innovations in grid integration technologies help optimise the use of fluctuating renewable energy outputs, ensuring continuous and efficient hydrogen production (Zachary et al., 2022).

Scaling up production processes for electrolyzers and other hydrogen technologies is critical to achieve economies of scale and reduce costs. Strategic investments in RDI foster collaboration between academia, industry, and government, driving breakthroughs that accelerate the commercialisation of green hydrogen technologies globally.

5.7 Hydrogen standardisation and safety

Hydrogen standardisation and safety are paramount to ensure the reliability, interoperability, and public acceptance of hydrogen technologies. Establishing international standards is crucial for harmonising technical specifications across hydrogen production, storage, transportation, and utilisation. Standardisation efforts aim to facilitate global trade in hydrogen and hydrogen-based products while ensuring compatibility and reliability of equipment and infrastructure (Kumar et al., 2024). Safety regulations play a vital role in mitigating risks associated with hydrogen handling, storage, and utilisation (Li et al., 2022). Developing robust safety standards and certification processes ensures the protection of workers, communities, and the environment. Certification and testing protocols verify compliance with safety standards, promoting confidence in hydrogen technologies among stakeholders.

Public awareness and education initiatives are essential to increase understanding of hydrogen safety principles and practices. Educating stakeholders including industry professionals, policymakers, emergency responders, and the public on safe hydrogen handling and usage fosters a supportive regulatory environment and encourages responsible deployment of hydrogen technologies (Tchouvelev et al., 2019).

By prioritising hydrogen standardisation and safety alongside RDI, stakeholders can pave the way for the widespread adoption of green hydrogen as a clean and sustainable energy solution. These efforts contribute to achieving global energy transition goals and addressing climate challenges effectively.

6 Efforts of African countries in adopting green hydrogen

Green hydrogen is rapidly gaining popularity amongst African countries and the efforts of some of the countries in the adoption of green hydrogen cannot be overlooked. Both South Africa and Morocco are making significant efforts in order to position themselves as leaders in the adoption of green hydrogen in Africa (Pinto and Chege, 2024).

6.1 South Africa's green hydrogen initiatives

South Africa, with its significant renewable energy resources and industrial capabilities, has emerged as a key player in the development and adoption of green hydrogen (Pinto and Chege, 2024). Recognizing the potential of green hydrogen to transform its energy landscape, reduce carbon emissions, and create economic opportunities, South Africa has launched several initiatives aimed at positioning itself as a leader in the global hydrogen economy. South Africa's vast renewable energy resources are central to its green hydrogen strategy. The country enjoys abundant solar and wind resources, particularly in the Northern Cape region, which is one of the sunniest places on earth. This makes it an ideal location for large-scale solar photovoltaic (PV) and concentrated solar power (CSP) projects. Additionally, the coastal regions are well-suited for wind energy projects, further enhancing the country's renewable energy potential (Gaeatlholwe, 2021). Some of South Africa's initiatives regarding green hydrogen include:

- Hydrogen South Africa (HySA) Programme Launched in 2008 by the Department of Science and Innovation (DSI) which aims to develop and guide innovation along the hydrogen and fuel cell technology value chain (Roos and Wright, 2020). The programme focuses on developing efficient and cost-effective methods for hydrogen production, primarily through water electrolysis using renewable energy, and establishing infrastructure for storage and distribution (Roos, 2021), advancing fuel cell technologies for various applications, including transportation, stationary power generation, and portable power and demonstrating integrated hydrogen systems in real-world applications to showcase their feasibility and benefits.
- Hydrogen Valley Initiative The Hydrogen Valley Initiative, a collaborative effort between the DSI, Anglo American, Bambili Energy, and Engie, aims to create a hydrogen corridor linking the country's industrial hubs (Grobbelaar and Ngubevana, 2022). Similar to the HySA programme, it seeks to develop a hydrogen production and distribution network along the corridor, promote the use of hydrogen in various sectors, including mining, transportation, and manufacturing and attract investment and create jobs in the emerging hydrogen economy.

There are also renewable hydrogen production projects that South Africa has initiated aimed at producing green hydrogen using renewable energy. They include projects like the Boegoebbai hydrogen project and the Prieska Power reserve project (Kneebone, 2022; Kritzinger and Snyman, 2022).

To support the development of the hydrogen economy, the South African government has introduced the National Hydrogen strategy. The strategy outlines the country's vision for becoming a leading producer and exporter of green hydrogen and its derivatives. It emphasizes the development of domestic hydrogen markets, international partnerships, and the establishment of a conducive regulatory environment. Incentives and Funding: The government has introduced incentives and funding mechanisms to encourage investment in hydrogen technologies and infrastructure. These include tax breaks, grants, and low-interest loans for hydrogen projects (Bessarabov et al., 2012; Bessarabov and Pollet, 2022).

6.1.1 International collaboration

South Africa actively seeks international partnerships to advance its hydrogen agenda. Key collaborations include the agreements with Germany to develop green hydrogen projects, focusing on technology transfer, capacity building, and market development (Brauner et al., 2023). South Africa also partnered with Japanese companies and research institutions aim to advance hydrogen production technologies and explore potential markets for South African green hydrogen (Patel, 2020).

6.1.2 Challenges and opportunities

While South Africa's green hydrogen initiatives hold great promise, several challenges need to be addressed:

- Significant investment is required to develop the necessary infrastructure for hydrogen production, storage, and distribution (Ayodele and Munda, 2019).
- Reducing the cost of green hydrogen production to make it competitive with fossil fuels remains a key challenge.
- Establishing a clear and supportive regulatory framework is essential to attract investment and ensure the safe and efficient development of the hydrogen economy.

Despite these challenges, the opportunities for South Africa are substantial. By leveraging its renewable energy resources, industrial capabilities, and strategic location, South Africa can become a major player in the global green hydrogen market. The country's initiatives not only aim to reduce carbon emissions and enhance energy security but also to create economic growth and job opportunities in the emerging hydrogen sector.

6.2 Morocco's green hydrogen strategy

Morocco has emerged as a leader in green hydrogen within Africa, establishing the National Hydrogen Commission in 2019 to formulate a comprehensive strategy for green hydrogen production and use. Leveraging its renewable energy capacity, Morocco aims to play a significant role in the global green hydrogen market (van Wijk et al., 2019). The country's robust renewable energy infrastructure, including projects like the Noor Ouarzazate Solar Complex and Tarfaya Wind Farm, provides a reliable and scalable energy source for green hydrogen production (Bibih et al., 2024; Gawusu and Ahmed, 2024). These initiatives underscore Morocco's strong commitment to advancing green hydrogen technologies. Additionally, through projects like Green H2A, in collaboration with international partners, Morocco plans to produce green hydrogen for domestic consumption and export, supported by agreements with European nations such as Germany to develop production facilities and export routes (Weko et al., 2024).

6.3 Key projects in African green hydrogen development

In the framework of green hydrogen adoption in Africa, ongoing projects are pivotal in shaping the region's energy landscape. One notable initiative is the Sahara Green Hydrogen Project, spearheaded by a consortium of international and local partners. This project aims to harness the vast solar energy potential of North Africa, particularly in Morocco and Algeria, to produce green hydrogen for domestic use and export (Tiar et al., 2024). Another significant project is the Hydrogen Initiative in Egypt, which focuses on utilizing renewable energy sources along the Nile Delta region. This initiative aims to establish a sustainable hydrogen economy by leveraging both solar and wind resources abundant in the area and also make the country a potential supplier of low-carbon hydrogen for Europe owing to its proximity and its large renewable energy potential (Ruseckas, 2022). The initiative not only aims at domestic energy security but also positions Egypt as a key player in the international green hydrogen market, catering to Europe's increasing demand for clean energy.

These ongoing projects underscore the growing momentum towards green hydrogen adoption in Africa, highlighting strategic investments and collaborative efforts aimed at achieving energy security and sustainability goals.

7 Conclusion

The adoption of green hydrogen in Africa offers promising prospects for a sustainable and low-carbon future especially due to the rapid increase in population which automatically increases the energy demand in the continent. Green hydrogen would be advantageous to African countries in several sectors and would be a better fuel compared to conventional fuels. Despite the abundance of renewable energy resources, the continent still faces challenges in harnessing them. Lack of infrastructure, financing, and political issues will have all hindered the growth of renewable energy in Africa. Additionally, many African countries still rely heavily on fossil fuels for their energy needs. However, recent years have seen a growing focus on renewable energy in Africa, with increased investments and policy support aimed at unlocking the vast potential of renewable energy resources on the continent. Addressing these challenges will require collaboration and support from international partners, as well as a commitment from African governments to prioritize and invest in green hydrogen development.

South Africa and Morocco's efforts in adopting green hydrogen demonstrate their commitment to sustainable energy and climate action. Through strategic policies, investments in renewable energy, and international collaborations, these countries are paving the way for a green hydrogen economy. Their initiatives serve as a model for other African nations and highlight the continent's potential to contribute significantly to the global green hydrogen landscape. Although it may take some time due to the basic amenities and immediate requirements that African countries must address first, tackling each of these difficulties will be advantageous to the continent and its residents in the long term. African countries may use these chances to establish a sustainable and low-carbon economy with the correct policies, investments, and technical knowledge.

In so doing, green hydrogen may be developed in Africa and could also be used as a substitute for fossil fuels thus reducing the emission of greenhouse gases which causes the depletion of the ozone layer and which may in turn reduce global warming in general.

Author contributions

EO: Conceptualization, Writing–original draft, Writing–review and editing. JD: Methodology, Supervision, Writing–original draft, Writing–review and editing. OK: Methodology, Supervision, Writing–review and editing. ES: Investigation, Methodology, Supervision, Writing–review and editing. OA: Conceptualization, Investigation, Methodology, Project administration, Supervision, Visualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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