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PERSPECTIVE

Navigating the current landscape of green hydrogen, its potential, and challenges: a South African perspective

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Abstract

The main aim of this paper is to give an overview of the current landscape of the green hydrogen (GH_2) developments in South Africa and delve into possible barriers and opportunities. With this intention, a detailed overview of GH_2 production, storage, and its application was integrated. This is done through detailed assessment of the global and local literature and other key documents such as research reports, policy documents and other documents associated with GH_2 economy. As global communities' transition from fossil fuels to renewable energy sources, GH_2 is identified as a key solution to decarbonize hard-to-abate sectors such as the transport, chemical industry, and agriculture. Green hydrogen is produced using renewable energy sources such as solar and wind; with the application of electrolysers which split water into hydrogen and oxygen. With South Africa endowed with wind and solar power generation resources, the country is earmarked as one of the potential frontrunners of the GH_2 economy. Despite its potential, it is argued that South Africa still lacks financial resources, technology, and labour force of the correct skills to rapidly peruse the GH_2 economy. Currently, there are 24 GH_2 projects proposed with one hydrogen valley across three provinces. As a country with one of the highest unemployment rates, the paper highlights socio-economic prospects and details the government's intentions to reskill and upskill labour force to address the identified skills deficit for the GH_2 economy. Furthermore, South Africa possesses critical minerals such as platinum and iridium, which are essential to produce electrolysers and fuel cells. With this immense potential of the GH_2 economy in South Africa, the paper also delves into potential challenges such as water requirements, increased demand of critical minerals, energy security concerns, financial implications, as well as environmental and biodiversity impacts. Furthermore, the paper provides strategic recommendations pertaining to technological advancement and cost reduction through research and development, investment and financial mechanisms, public–private partnerships and development of government policy and regulatory support to accelerate the GH_2 economy that enable a national just transition.

1. Introduction

Conventional hydrogen (H_2) has been conceptualized as an energy carrier in the 1970s (Stamm *et al* 2023). It exhibits an outstanding energy storage capacity of 120 MJ kg^{-1} in both liquid and gas form, which is more than the energy storage capacity of natural gas, crude oil, and bituminous coal which exhibits 47, 43, and 26 MJ kg^{-1} respectively (Abe *et al* 2019, Ma *et al* 2024). Conventional hydrogen is produced using steam reformation, autothermal reforming, and partial oxidation. These methods are technologically advantageous, with steam reforming proven to be the most economical method. However, the methods utilize natural gas, coal, and oil which contribute to carbonization and exhaustion of finite resources. Since conventional methods release greenhouse gas (GHG) emissions, contemporary methods such as carbon capture and storage and electrolysis with nuclear power have been adopted to reduce the carbon footprint (Abe *et al* 2019, Fopah-Lele 2022). Although this is the case, the production of green hydrogen (GH_2) is seen as one of the global solution to the climate crisis, energy insecurity, and socio-economic development (Kalt *et al* 2023). Green hydrogen exhibits high utilization efficiency, and in terms of toxicity and fire hazards, it is considered the safest type of fuel (Abe *et al* 2019, Fopah-Lele 2022). It is also viewed as a critical energy carrier to decarbonize hard-to-abate sectors such as the transport sector by serving as clean fuel and the agricultural sector by serving as feedstock for the production of ammonia (Ishaq *et al* 2022, Zuben *et al* 2022). Green hydrogen can also be utilized as feedstock to produce various chemicals, pharmaceutical products, steel, and iron (Zuben *et al* 2022).

It is argued that GH_2 will not only decarbonize hard-to-abate sectors but also serve as a contingency plan by storing energy, as renewable energy resources are intermittent (Ma *et al* 2024). As a country endowed with renewable resources, South Africa has been earmarked as one of the potential GH_2 global frontrunners post Paris Agreement, thus sparking hopes for an African hydrogen revolution. The country has since attracted several foreign investments (Salgmann *et al* 2023, The Presidency Republic of South Africa 2023), and conceptualized a total of 24 GH_2 and green ammonia projects for local and international supply and local job creation (The Presidency Republic of South Africa 2023). Although there's potential for the development of a lucrative GH_2 economy in South Africa, this relies on factors such as advanced technology, sufficient funding, efficient pipeline systems and a wide range of resources such as energy, water, minerals (Kalt *et al* 2023). Conversely, South Africa remains challenged due to limited financial resources, infrastructure and the much needed technologies (Moorthy *et al* 2019, The Presidency Republic of South Africa 2023).

To overcome the above-mentioned challenges, the evolving bilateral hydrogen partnership between Germany and South Africa is set to play a significant role. This partnership aims to facilitate a high-level inter-ministerial dialogue to accelerate the implementation of GH_2 trade and allow both nations to leverage their resources (The National Hydrogen Council 2021, Kalt *et al* 2023). For example, As per the Just Energy Transition Investment Plan (JETIP), Germany is among the GH_2 investors in South Africa, however, the investments have faces criticism as they are predominantly loans (Union of Justice 2023). These investments are focused on production developments for import prospects and less on domestic purposes and acquiring more local socio-economic value. Therefore, this probed a debate amongst those who promote fossilist initiatives as to whether South Africa will benefit from its GH_2 economy (Kalt *et al* 2023).

Local GH_2 development is essential for driving positive environmental and socio-economic impacts such as the decarbonisation of hard-to-abate sectors, the creation of sustainable jobs, and enhanced industry competitiveness through export opportunities. Achieving this requires key enablers such as infrastructure development, technological advancements, and comprehensive policy adoption. Therefore, this research paper aims to assess the current state of GH_2 economy developments in South Africa, explore its potential socio-economic impacts, and identify potential key barriers and opportunities.

2. Overview of green hydrogen

Hydrogen is the lightest and most abundant element found on the planet with a molecular weight of 1.008 g mol^{-1} (Dawood *et al* 2020). It has recently gained popularity due to its high energy density, thus in cleaner form, it can be used as an alternative fuel to accelerate decarbonisation (Hassan *et al* 2023). However, almost 98% of the global hydrogen is still produced from natural gas, coal, and petroleum, while only 1% is produced from electrolysis (Saha *et al* 2024). As global communities transition away from fossil fuels (which are responsible for 78% of GHG emissions) to renewable energy sources that aid in climate resilience and support the development of low-carbon economies; GH_2 emerges as a pivotal pathway in the transition to net-zero carbon-related emissions. Many countries, particularly in the Global North, have already embarked on the deployment of GH_2 systems, rigorously advancing this technology by concentrating on its four critical phases: production, transportation, storage, and application (Dawood *et al* 2020). While the focus on these stages is critical; to fully capitalize on this energy vector, collaboration between various stakeholders and comprehensive policies, amongst other aspects, are also imperative (Sarpong-mensah 2023). This necessitate the need to understand its value chain and critical processes that can be adopted to enable its development and application.

2.1. Green hydrogen production

Green Hydrogen is produced through electrolysis, a process of splitting water into hydrogen and oxygen molecules using renewable energy (Sedai *et al* 2023, Webb *et al* 2023). The production of GH_2 by electrolysis entails the use of an electrolyser, a device that consists of a cathode and an anode submerged in an electrolyte, and when electricity is applied, this device produces hydrogen at the cathode and oxygen is produced at the anode (Nikolaidis and Poullikkas 2017, Bollmann *et al* 2023).

The types of electrolysers that are commonly used are alkaline electrolyser, proton exchange membrane (PEM) (Sarpong-mensah 2023), and solid oxide electrolyser (Atilhan *et al* 2021). Alkaline electrolyser is usually categorized by its high technological maturity and long service (Rampai *et al* 2024), and it utilizes electrolyte solutions such as potassium or sodium hydroxide (Baum *et al* 2022, Bollmann *et al* 2023). Solid Oxide electrolyser uses ceramics electrolytes and it operates at very high temperatures (500 °C–900 °C) to reduce electrical needs (Bollmann *et al* 2023). The PEM electrolyser has a small cell size, exhibits high current density, and has a wide power regulation range (Rampai *et al* 2024). The PEM electrolyser utilizes polymer electrolytes, and the cathode and anode are often platinum and iridium respectively (Kiemel *et al* 2021).

While electrolysis is the most environmentally sustainable method for producing GH_2, the method is energy intensive. However, due to renewable energy costs' potential to decline in the future (Hassan *et al* 2023), GH_2 could soon become competitive with other conventional types of hydrogen which are already established in the market (Nikolaidis and Poullikkas 2017). Due to the versatility of GH_2 to produce a range of green products and its capacity to store energy, this energy carrier signals a significant competitive edge (Nikolaidis and Poullikkas 2017, Hassan *et al* 2023).

2.2. Green hydrogen storage and transportation

Green hydrogen is argued to be an ideal solution for renewable resources intermittency, and it enables optimum energy storage and long-distance transportation. It can be stored and transported in various forms, either in a liquid state and gaseous state (physical-based storage) or solid state (by hydrogen carriers). Selecting hydrogen storage systems depends on the storage duration and the size of the product to be stored (Atteya *et al* 2023). Although GH_2 has numerous advantages, its storage poses several challenges. Given that hydrogen is flammable, leaks easily, has a wide flammability limit range of 4–75 vol% (Zhang *et al* 2020, Li *et al* 2022), safety precautions are essential when handling it. Various storage options include gaseous hydrogen storage, where hydrogen gas is often stored in a high-pressure vessel (Abdalla *et al* 2018, Faye *et al* 2022). Ideal high-pressure vessels are those with materials that are non-reactive, non-permeable, and have high tensile strength and low density (Abdalla *et al* 2018). Hydrogen can also be stored in liquid form where gaseous hydrogen is usually liquified for medium and large-scale storage (Hren *et al* 2023). Liquified hydrogen is typically required for short-term storage and high energy density applications (Atteya *et al* 2023). Hydrogen can also be stored in solid form where material-based systems are applied. This type of storage entails bonding hydrogen molecules with metals (pure or alloy) at ambient parameters to produce metal hydrides, thus promoting an easy process of hydrogen release and enhancing storage efficiency (Atteya *et al* 2023).

2.3. Green hydrogen applications

In general, conventionally produced hydrogen runs through various production chains. Green hydrogen, thereof, is a symbolic representation of decarbonisation across various production chains. As illustrated in figure 1, it can be applied in various applications as an energy vector and feedstock. It is an attractive potential transportation fuel, predominantly for aviation and shipping. However, the application of GH_2 in the transportation sector, is contingent of modernized engines which will inevitably increase the cost of the overall transportation industry (Qazi 2022, Zuben *et al* 2022). Another application of GH_2 that is currently a huge area of research is in fuel cell technology. A fuel cell is an electrochemical device that directly converts chemical energy into electrical energy by releasing water and heat as by-products (Baharuddin *et al* 2021, Maganza *et al* 2023). Although smaller fuel cells can be utilized to power mobile phones and computers, larger GH_2-based fuel cells can store power to later supply buildings such as hospitals, residences and schools as well as agricultural systems and manufacturing facilities (Zuben *et al* 2022), particularly those that are not connected to the grid (Baharuddin *et al* 2021). Fuel cells share similar characteristics as batteries; however, they are more advantageous as they can continue operation as hydrogen is supplied in real time. Conversely, batteries discontinue to operate the moment the reactants are consumed. More so, batteries are limited by external issues such as corrosion and material malfunctions (Zuben *et al* 2022).

Green hydrogen can also act as a feedstock to produce ammonia, the second most highly produced chemical with a global manufacturing capacity of 230 Mtpa (million tonnes per annum). About 80% of the ammonia produced is used in the production of fertilizers. Ammonia is, however, not limited to the production of fertilizers; it is also used in the manufacturing of explosives and other chemical commodities (Chatterjee *et al* 2021). Studies have discovered that ammonia can also be used as a direct fuel, however, it has a very low combustion intensity and direct ammonia fuel cells are currently at low technology readiness levels (Spatolisano *et al* 2023). Additionally, GH_2 can be used in the manufacturing of methanol (Qazi 2022), pharmaceutical products, iron and steel as well as fuel refining (Zuben *et al* 2022).

The above literature highlights the role that GH_2 can play in the global energy transition However, this can be realized by enabling factors that will be discussed later.

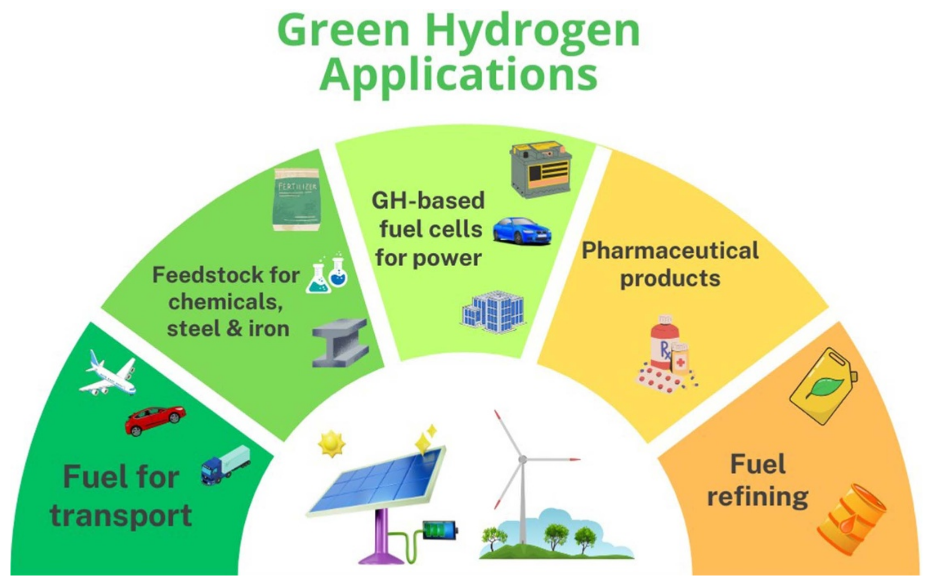

Figure 1. Green hydrogen application as a source of energy and feedstock across various sectors.

3. The current landscape of green hydrogen and its developments in South Africa

It has become imperative for South Africa not only to reduce its carbon footprint but also to address energy security and socio-economic challenges. Contemporary solutions such as GH_2 and leveraging abundant natural resources such as solar and wind power, present a significant opportunity to drive local growth. As shown in figure 2, South Africa is among the African countries with high irradiation. Most of the country's regions encounter over 2500 h of sunshine annually, with an average of 2025 kWh m^{-2} of total annual irradiation, thus equating to 5.55 kWh m^{-2} per day (Abdelrazik *et al* 2022, Overen and Meyer 2022, Dyantyi-Gwanya *et al* 2025). The province with the highest solar radiation is the Northern Cape, which exhibits 2282 kWh m^{-2} annually as opposed to 1786 kWh m^{-2} which is the least radiation exhibited by KwaZulu Natal (Abdelrazik *et al* 2022, Overen and Meyer 2022). Furthermore, South Africa has strong wind power potential in coastal areas with an altitude of 100 m which highlights the country's wind energy capabilities. The entire country has an average wind speed of 6 m s at an altitude of 10 m and a projected potential to produce 60 TWh of wind energy annually (Mostafaeipour *et al* 2020).

3.1. South Africa's hard-to-abate sectors in need of green hydrogen for decarbonisation

As the most carbon intensive country in Africa with high dependence on coal, there lies a need for strategic implementations to decarbonize local sectors (IRENA 2020, Eskom 2022). The local energy sector and the chemical sector have the highest GHG emitters, followed by the chemical sector. The energy sector has contributed a major share of almost 90% of the total national GHG emissions over the last three decades mainly due to coal-fired powered plants. Over 80% of the country's electricity is generated from coal (Hanto *et al* 2021), with the majority of the coal-powered plants located in the coal hub province, Mpumalanga (The Presidency Republic of South Africa 2023).

The local chemical sector was founded later in the 19th century due to the high demand for mining explosives. This led to the take-off of the sector which developed around the gasification of coal (Majozi and Veldhuizen 2015). The chemical sector, contributes about 13% of the total national GHG emissions (NBI 2019). It consists of a variety of sub-sectors including industrial chemicals, petrochemicals, plastics, and ammonia (Majozi and Veldhuizen 2015). The petrochemical sub-sector is divided into three groups; (i) olefins which are used as feedstocks to produce plastics, industrial chemicals, and synthetic rubber; (ii) aromatics which are used to produce synthetic detergents, dyes, and synthetic fibres; and (iii) synthesis gas which is used to produce methanol, diesel- and gasoline-range hydrocarbons (Speight 2019). The sector is highly competitive on a global scale, consisting of numerous manufacturing companies with the biggest key player being SASOL, followed by other leading players such as Renergen, BASF, AECI, and Afrox among others (InvestSA n.d.). From the above mentioned chemical companies, SASOL is argued to be responsible for 90% of the chemical sectors' GHG in South Africa, predominantly coming from Secunda and Sasolburg operations (NBI 2019).

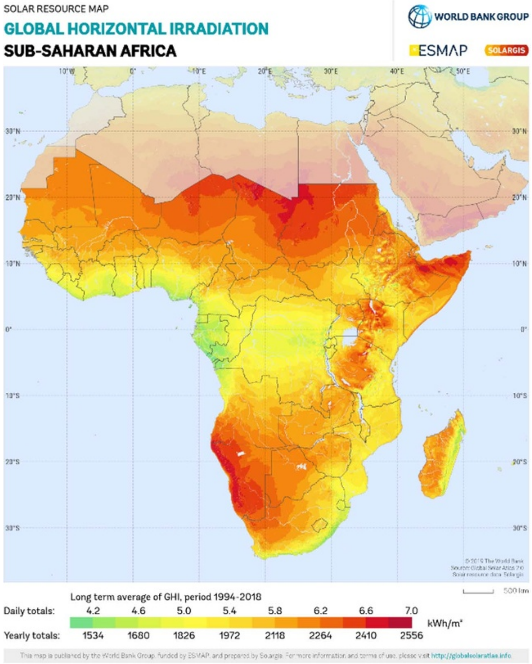

Figure 2. Global horizontal radiation of Sub-Saharan Africa (Global Solar Atlas, n.d.). Reproduced from Global Solar Atlas, CC BY 4.0. Map and data obtained from the "Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info.

It is against these observations that the JET-IP 2023–2027 endorses the GH_2 for applications in the power sector, the chemical production sector and as a commodity for local and international exports (The Presidency Republic of South Africa 2023). Similar to the energy and chemical sectors, GH_2 is aimed to also be applied in the transport sector which contributes significantly toward the total GHG emissions nationwide (Department of Transport 2017).

3.2. South African green hydrogen projects

3.2.1. Green hydrogen and green ammonia projects in South Africa

There is currently a total of 24 GH_2 projects planned for short- and medium-term execution. From these projects, priority projects that are registered with the International Solar Alliance are shown in table 1 with their respective production as per each green product (see footnote) (South African Government 2022). These priority projects have been granted with the Strategic Integrated Project status, denoting a high social and economic significance to the country and contribution to strategies and policies involving infrastructure developments (The Presidency Republic of South Africa 2023). Amongst these projects, the green hydrogen valley and the Boegoebaai port and green hydrogen Cluster project will be instrumental in aiding South Africa towards becoming a leading GH_2 exporter in Africa (Scholvin *et al* 2025).

Unlike landlocked countries, the coastal nature of South Africa serves as an advantage, with several of the GH_2 projects being anticipated for location in coastal regions for ports utilization and export prospects. Furthermore, South Africa has international maritime routes that could be leveraged in implementing a competitive GH_2 ecosystem (Bhatt *et al* 2023, Notteboom and Haralambides 2023).

Green hydrogen valley is integrated with three hubs within three provinces (Limpopo, Gauteng, and KwaZulu-Natal) to serve as an industrial cluster (Media Hydrogen Revolve 2022). Within the three provinces, there are industrial hubs that the valley is aimed to connect as shown in figure 3. The three hubs include the following (South African South African Department of Science and Innovation 2021, Stamm *et al* 2023):

(i) Johannesburg hub—the hub extends to Rustenburg and Pretoria. Around these areas, chemical, steel, cement, and iron production sites are located. These industries are required to shift towards low-carbon feedstock. The supply will also include the mobility sector, predominantly for fuel cell trucks along the N3 freight corridor.

(ii) Durban/Richards Bay hub—located in the coastal areas which provides potential for GH_2 export activities. Durban has the biggest port in the country, and with the rigorous port activities already taking place, low-carbon fuels are required. The pulp and paper industry within the region may also benefit from this clean hydrogen supply.

Table 1. Prioritized GH_2 projects and their production capacity.

Green hydrogen project	Projected outcome	Commercial operation date	Production (ktpa)	References
Boegoebaai port and green hydrogen cluster	✓ Has the potential to become South Africa's green hydrogen export hub. ✓ Aimed to produce green hydrogen and ammonia. ✓ Projected to deliver an initial 5GW of hydrogen by 2035. ✓ Projected to create 6000 direct jobs.	—	—	(Grobbelaar and Ngubevana 2022, Largue 2023)
HIVE energy/Coega green ammonia project	✓ Projected to produce 780 000 tonnes of green ammonia per year. ✓ Aimed to drive the development of multi-functional storage facilities.	2028	237 Ktpa GNH_3	(Biogradlija 2022, Largue 2023, The Presidency Republic of South Africa 2023)
HyShiFT secunda	✓ Aimed to produce eco-friendly aviation fuels using existing Sasol Secunda renewable energy.	August 2026	16.4 Ktpa GH_2/36.1 Ktpa sustainable aviation fuel	(Biogradlija 2022, The Presidency Republic of South Africa 2023)
Prieska power reserve	✓ For green hydrogen and ammonia production by combining high-yielding renewable solar and wind energy. ✓ Projected to create 10 500+ jobs in the first phase with the inclusion of vulnerable groups.	2026/7	14 ktpa GH_2/80 ktpa GNH_3	(Biogradlija 2022, South African Government 2022, The Presidency Republic of South Africa 2023)
Sasolberg green hydrogen project	✓ Projected to produce 5 tons of green hydrogen daily provided the availability of 60 MW of renewable energy.	—	—	(Biogradlija 2022)
South African hydrogen valley	✓ The first integrated hydrogen ecosystem with three hubs in three provinces (Limpopo, Gauteng, and KwaZulu-Natal). ✓ Projected to create up to 30 000 jobs per year with the potential to contribute over \$8 billion to the South African GDP by 2050.	2030	185 Ktpa GH_2 by 2030	(South African Department of Science and Innovation 2021, The Presidency Republic of South Africa 2023)
Atlanthia project (Phase 1)	✓ Planned to produce GH_2 and ammonia in Freeport Saldanha from solar and wind energy and contribute to the economy.	2027	7.3 Ktpa GH_2/36.5 Ktpa GNH_3	(South African Government 2022, The Presidency Republic of South Africa 2023)

(Continued.)

Table 1. (Continued.)

Ubuntu green energy project (Phase 1)	✓ To produce GH_2 and ammonia from solar and wind energy and contribute to the economy.	2026	7 Ktpa GH_2/3.5 Ktpa GNH_3	(South African Government 2022, The Presidency Republic of South Africa 2023)
Saldanha green hydrogen project	✓ To produce GH_2 with ArcelorMittal South Africa's Saldanha Works steel plant as an anchor offtake	2027/8	60–80 Ktpa GH2	(The Presidency Republic of South Africa 2023)
Upilanga solar and green hydrogen park (Phase 1)	✓ To produce GH_2 from solar energy and contribute to the economy.	—	19.8 Ktpa GH_2	(South African Government 2022, The Presidency Republic of South Africa 2023)

*Note: Ktpa (kiloton per annum), * GH_2 (Green hydrogen) * GNH_3 (Green ammonia).*

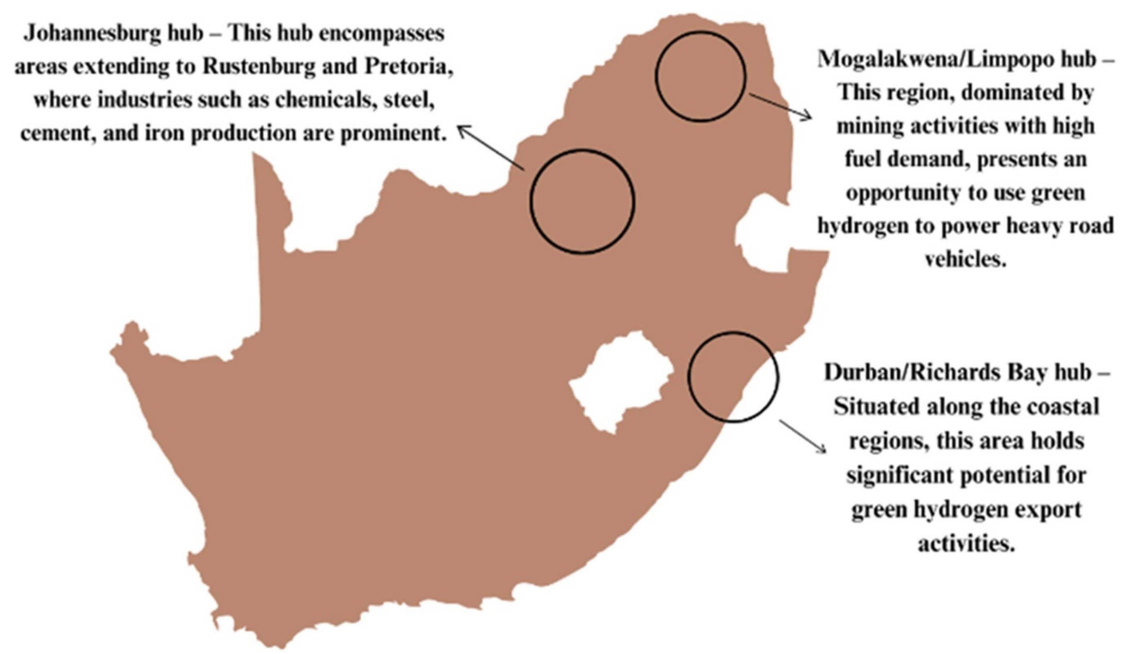

Figure 3. Illustration of the three green hydrogen valley hubs in South Africa.

(iii) Mogalakwena/Limpopo hub—located in areas that are dominated by mining activities with high fuel demand, thus GH_2 can be utilized to fuel heavy road vehicles.

The Boegoebaai Port and GH_2 cluster project will be located relatively close to the mining and agriculture sectors (The Department of Trade Industry and Competition 2022a). It is suggested that this project will further be extended to the Boegoebaai port and Rail Infrastructure Project which entails construction of a 550 km of railway that links the port with mines and industrial areas within the Northern Cape province. The port will, as alluded, improve connectivity within the Northern Cape Province and provide the logistics for GH_2 and green ammonia as well as manganese and other commodity exports in the province (Bains 2023). This is anticipated to provide much needed economic improvement systems for the Northern Cape province, as it remains one of the poorest in the country.

3.2.2. Green hydrogen mobility projects

In May 2022, Anglo-American unveiled the world's first and largest hydrogen-powered mine haul truck. The hydrogen-powered truck was designed by Anglo American and First Mode in Seattle (USA), as a pilot for daily operations at Mogalakwena platinum group metal (PGM) mine in South Africa. The novel truck has a 2 MW hydrogen-battery system which generates more power than its diesel counterpart that uses ~3000 l of diesel per day leading to ~8 tons of CO_2 generation. The GH_2 is supplied from the 3.5 MW GH_2 plant on site

(Geldenhuys 2022, Cole 2023). Diesel haul trucks contribute 80% of the total emissions at Anglo American owned and operated mines globally, thus rolling out a diesel-powered truck with the zero-emission haulage truck system will aid in decarbonizing the company (Anglo American 2022, Geldenhuys 2022).

Furthermore, In October 2023; Sasol, Anglo American Platinum, and BMW Group formed a consortium to catalyse the decarbonisation of the transport sector by developing a local GH_2 mobility ecosystem in South Africa. The consortium will launch a pilot fleet of GH_2 fuel cell electric vehicles, with each partner playing a key role. Sasol will supply the GH_2 fuel, Anglo American Platinum will provide the metals used in GH_2 technology manufacturing, and BMW will contribute with hydrogen fuel-cell electric vehicles. Together, these private stakeholders aim to support the development of infrastructure for decarbonizing the economy, drive demand for critical metals, and create jobs (BMW Group 2023).

4. Socio-economic prospects

South Africa possesses valuable resources with the potential to enhance its competitiveness in the global GH_2 supply chain. These include critical minerals essential to the GH_2 value chain, which can play a key role in building a strong local GH_2 ecosystem. In addition to the right manufacturing scale, this could lead to increased job creation and energy security (IRENA 2023a).

4.1. Green hydrogen local demand and exports prospects

Driven by their significant industrial demands, the European Union, Japan, South Korea, and the United Kingdom are expected to emerge as the leading importers of GH_2 to meet their Net-zero targets and grow their economy (The Department of Trade Industry and Competition 2022a). The European Union is projected to import 10 Mtpa by 2030, Japan and South Korea are expected to import 0.3 Mt each from 2030, and depending on the local production, the United Kingdom is expected to import 0.7 Mt by 2050 (The Department of Trade Industry and Competition 2022a).

Contingent to available financial and technological resources, South Africa holds potential to become one of the above-mentioned global exporters with its location positioned along the Indian and Atlantic shipping routes. With GH_2 export projections ranging from 1.9 to 8.0 Mtpa, the nation could capture 8%–10% share of the global market for ammonia and methanol fuels applicable in the shipping industry. With the realization of the above projections, South Africa has potential to secure 7% of the global GH_2 export market share at 1.9 Mtpa scenario. Using the same base scenario, South Africa stands to compete with the United Arab Emirates as shown in figure 4. However, with 3.0 Mtpa, South Africa can acquire $\sim$10% of the global market share and become competitive with Morocco, Russia, and Chile. With 4.0 Mtpa that can lead South Africa to acquire 15% of the market, the country can be set to compete with Saudi Arabia and Australia. Although this highlights South Africa's potential success, Dagnachew *et al* (2024) strongly asserts that there is a lot of interest directed towards African GH_2 exports to European countries. As this is not inherently wrong, the author highlights that the current clean energy resource development in Africa has neo-colonial characteristics and Africa should avoid myopic focus on GH_2 exports to the European market. To conclude, the above mentioned projections are dependent on the carbon markets, reduction of production cost, availability of adequate infrastructure, and various incentives to balance the price parity (The Department of Trade Industry and Competition 2022b).

4.2. Critical minerals

The are about 51 critical minerals identified for the energy transition across the board. However, for the application of GH_2 value chain, PGMs, specifically iridium, platinum, and titanium, are the most required minerals, particularly for the production of PEM electrolysers as shown in figure 5(a) (IRENA 2023a). Minerals are generally concentrated in specific geographic locations and most of the global platinum and iridium are predominantly extracted in South Africa as shown in figure 5(b). Thus, South Africa does not only have the potential to play a dominant role in the production and export of GH_2 but in exporting of platinum and iridium as well. PEM electrolysers are currently being scaled up more compared to their counterparts. This is due to their high flexibility under pressure and their high power density systems, thus denoting a window of opportunity for the nation to export platinum and iridium as demands rise (Kiemel *et al* 2021).

Iridium is a co-product of platinum and palladium production and its content in these minerals is 1% on average, making it one of the rarest secondary metals globally. It is estimated that between 1990–2013, only 2.2–4.9 tons of iridium was produced, and due to its geographical concentration, South Africa makes up over 70% of its global market (Minke *et al* 2021). Unlike iridium, platinum demands are widespread in the manufacturing of grid-scale batteries, electrolysers, and electric vehicle chargers, this denotes more demands in the future (International Energy Forum 2023).

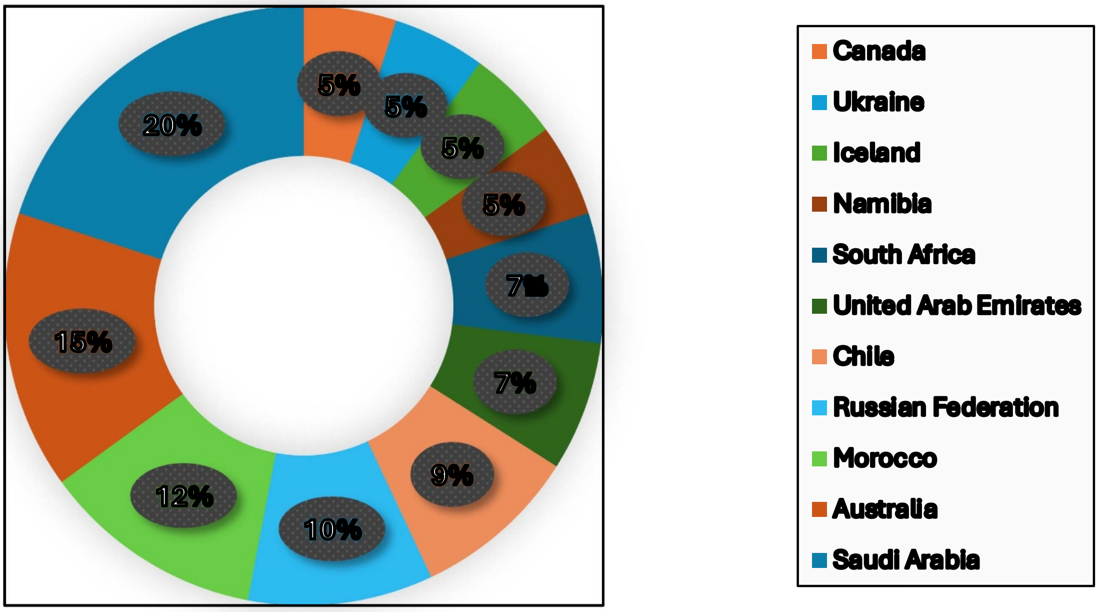

Figure 4. Green hydrogen global export market share at 1.9 Mtpa scenario. Source data: (The Department of Trade Industry and Competition 2022b).

Currently, South Africa is the largest global exporter of platinum. In 2021, the country exported platinum worth USD 24.5 billion. In the same year, platinum was the most exported product in the country with most of it exported to the United States of America, Japan, the United Kingdom, Germany, and Hong Kong respectively (OEC 2021b). In the same year, South Africa exported USD 501 million worth of titanium ore to the Netherlands, the United States, Saudi Arabia, Japan, and Chinese Taipei respectively (OEC 2021c). Iridium exports were recorded as a collective with osmium and ruthenium in a semi-manufactured form. In 2021, USD 55.3 million worth of the joint products were exported mainly to the United Kingdom, Germany, the United States, India, and Hong Kong (OEC 2021a).

Interestingly, iridium has a record of volatile prices due to its versatile electro-chemical applications. Over 26 years, from 1995–2021, the price of iridium has increased rapidly, particularly during and after COVID-19 (SFA Oxford 2021, IRENA 2023b). As the GH_2 economy grows, South Africa may potentially experience growth in exports to China and Japan, as the two nations have been the leading electrolyser manufacturers and exporters in recent years. More so, China currently accounts for ∼40% of the global manufacturing capacity (IRENA 2023b). While these economic opportunities offer significant advantages for South Africa, the extraction of critical minerals could lead to resource depletion. Therefore, strategies and policies for export prospects must prioritize ethical management and preservation.

4.3. Social impacts

South Africa exhibits one of the highest unemployment rates of 31.9% as of the third quarter of 2023 (Statistics South Africa 2023), and the development of the GH_2 economy is targeted to reduce unemployment rates. The government aims to achieve this by putting efforts on producing newly skilled graduates, reskilling the labour force in the energy sector, and creating cohesive cooperation between industry and educational institutions (The Presidency Republic of South Africa 2023). Although, Scholvin *et al* (2025) maintains that education and training have received considerable attention in South Africa, there remains a need to highlight the skills mismatch between the current national higher education curricula and required green skills in the industry. Green skills are defined as technical expertise, knowledge, principles, and approaches that are essential to contribute to a sustainable economy (Zubir *et al* 2021). To address the existing gap, several interventions have been proposed, and these interventions are discussed in the following sub-section.

4.3.1. Workforce development

The 2023 Energy Skills Roadmap South Africa report provides a detailed list of energy-related courses offered in the country, this list highlights both the technical and soft skills required (SANEA 2023). Globally, universities are expected to produce graduates with a strong interest in the green economy. However, South Africa is prioritizing inclusivity by extending opportunities to technical vocational education and training (TVET) college graduates as outlined in the green hydrogen TVET Ecosystem Just Transition Strategic

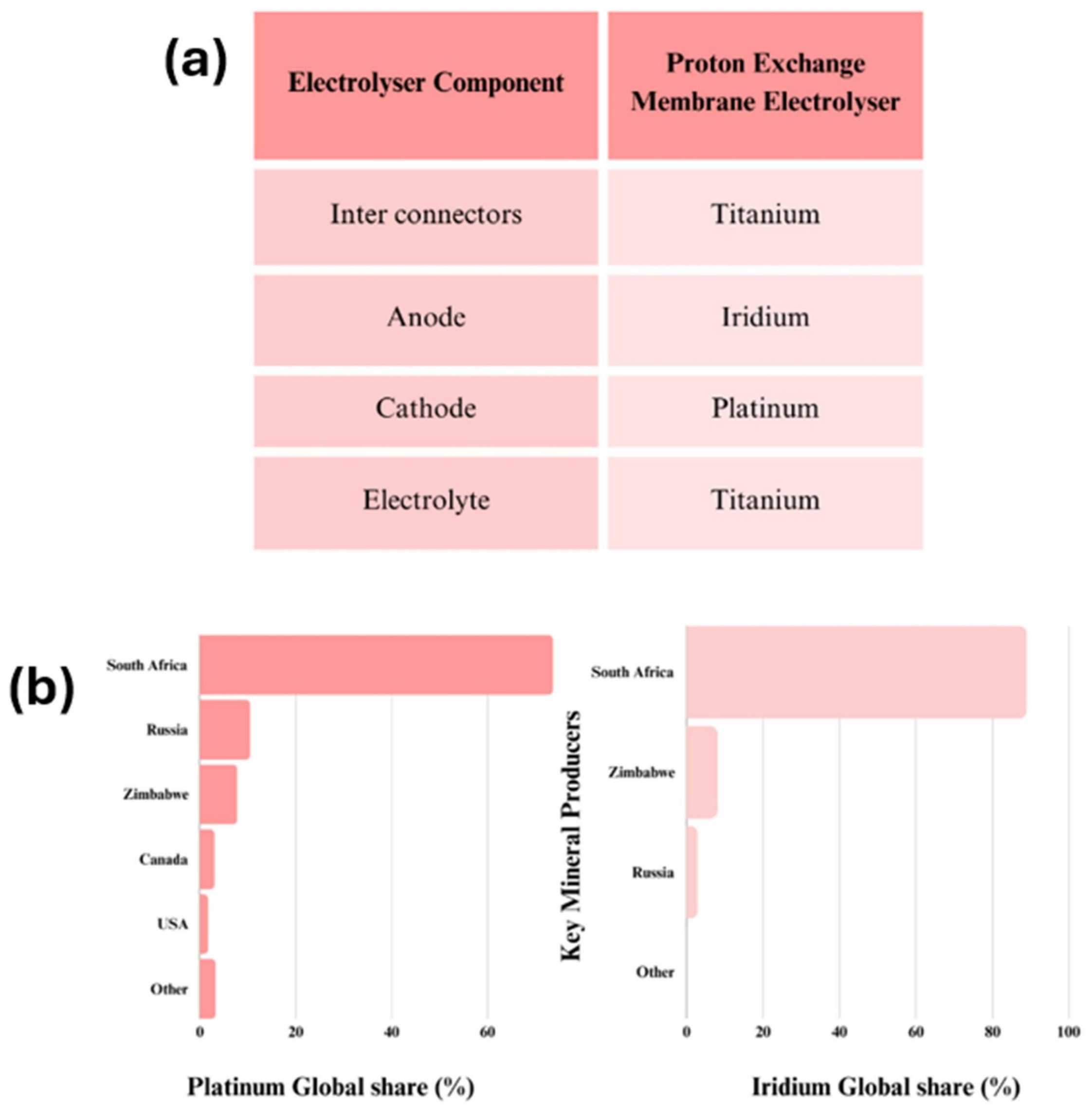

Figure 5. (a) Illustration of various critical minerals needed to produce the electrolysers. Source data: (Laveissiere *et al* 2022) (b) countries where iridium and platinum are concentrated. Source data: (IRENA 2023a).

Framework (Department of Science and Innovation 2022). The government has high ambitions for the TVET ecosystem and requires it to produce an adequate number of trained artisans and technicians to meet future skills demands. This ecosystem is identified as an effective route to support and include the youth to provide a range of low, intermediate, and high-level skills that will supply the GH_2 labour market (Department of Science and Innovation 2022).

The TVET ecosystem is, however, yet to reach the growth anticipated by the National Development Plan 2030 to produce a more skilled labour force. In 2019, the ecosystem had under 700 000 enrolments which was a 4.5% decline from 2016. The decline in enrolments for 3 year qualifications is attributed to students struggling with the technical requirements of these courses. While the targeted enrolment is set at 1.2 million by 2030, the government has also identified a gap between vocational training and industry needs. The ecosystem has yet to fully implement green skills, and to address this challenge, the green hydrogen TVET ecosystem just transition strategic framework has outlined three key horizons as follows (Department of Science and Innovation 2022):

(i) Evaluate and critique the current institutional systems.
(ii) Introduce a new system and phase out the old system.
(iii) Develop the new system to grow into dominance so that TVET skill can penetrate the GH_2 economy to alleviate unemployment amongst the youth.

Table 2. Green hydrogen financial initiatives for the development of the South African GH_2 economy.

GH_2 funding initiative	Description	reference
KfW Development Bank-Industrial Development Corporation (IDC) Programme.	A EURO 23 million fund aimed at accelerating South Africa's GH_2 economy by propelling large-scale production and use of GH_2 particularly for projects such as hydrogen-powered heavy-duty vehicles, aviation fuel, and green ammonia for export.	(KfW 2023, The Presidency Republic of South Africa 2023)
Just Energy Transition Partnership (JETP)	A minimum of ~USD 0.7 billion from a total of USD 11.6 billion pledge has been proposed for the GH_2 development.	(The Presidency Republic of South Africa 2023)
Power-to-X (PtX) Development Fund	A EUR 270 million fund is open to South Africa, Brazil, Egypt, Georgia, India, Kenya, and Morocco to support already developed GH_2 projects that may require additional funds to complete outstanding tasks. At this point, South Africa has more suitable projects to qualify for this fund.	(Creamer 2024)
sa-h_2 fund	A USD 1 billion target fund was initiated with EURO 50 million seed funding. This fund is aimed at enabling the development of the South African GH_2 sector and circular economy.	(Sanlam 2023, The Presidency Republic of South Africa 2023)

The African continent has highest youth population, with 70% of the Sub-Saharan population consisting of people under the age of 30 (Agyekum 2024). Thus, Agyekum (2024) asserts that, the African youth present an opportunity to drive the GH_2 development of the continent which will require skilled youth, particularly in countries such as South Africa. Additionally, the South African Department of Employment and Labour and the energy sector ought to actively engage and articulate the skills required to promote alignment across the industry (Department of Science and Innovation 2022).

5. Financing and investments

Given the potential of the local GH_2, South Africa remains financially challenged to set up a competitive GH_2 industry on its own accord. The GH_2 projects proposed require approximately ZAR 300 billion (~USD 15.5 billion) to be launched (Salgmann *et al* 2023, The Presidency Republic of South Africa 2023). Several initiatives have been undertaken by nations that will serve as South Africa's primary market. These initiatives include trade relations and funding programs aimed at accelerating GH_2 development in the country. Among these nations, Germany has demonstrated strong enthusiasm for supporting the growth of South Africa's GH_2 economy (The Department of Trade Industry and Competition 2022b). Financial initiatives that have been reported are listed in table 2.

Although the funds provide a strong foundation for developing South Africa's GH_2 economy, GH_2 projects often encounter off-take challenges, especially in the early stages. These challenges have caused termination of ~80% of global GH_2 projects, at an average cost of USD 1 billion (The Presidency Republic of South Africa 2023). Additionally, the predicament in South Africa is that the funding programs are not inclusive of first loss equity, a subordinated share of the investment aimed to absorb any unexpected losses in the event of unsuccessful project take-off. Like the JETP, the funds primarily consist of concessional loans. Therefore, South Africa will likely require additional investment to meet its financial targets for fully developing the GH_2 economy. With rising competition, the country must also secure grants to strengthen its market position against other nations (The Presidency Republic of South Africa 2023).

It is important to note that the development of South Africa's GH_2 economy should not be driven by green extractivism, which focused solely on export prospects and the transfer of GH_2 to the Global North. A larger share must contribute to local socio-economic value to truly symbolize the 'Just' in the energy transition. This can be achieved if South African decision makers adopt a bottom–up, people-cantered energy transition, thus creating a pathway for fair and inclusive decarbonisation (Kalt *et al* 2023).

6. Potential barriers and recommendations for the development of the South Africa green hydrogen economy

The global implementation of the green economy through the deployment of various low-carbon technologies has the potential to have a positive and negative impact on the environment. The positive impacts include reduction of GHG emissions (Agyekum 2024), improving energy efficiency, and improvement of waste management (Gökgöz and Güvercin 2018). Some of the anticipated negative impacts are increased by mining activities caused by increased mineral demands (Sonter *et al* 2020), and increased use of water and land which will eventually approach physical limits (Arent *et al* 2014, Hickel and Kallis 2020). With the potential that South Africa has, it is imperative to understand, strategically plan, and manage resources as well as additional key aspects required for the GH_2 economy (Woods *et al* 2022). In this interest, as the global demand for GH_2 is expected to reach 530 Mt by 2050, the demand for water, minerals and other resources will inevitably increase (Tonelli *et al* 2023), thus leading to potential barriers highlighted in this section. In addition, this section also delves into proposes strategic recommendations that can be adopted to propel this economy. The potential barriers that can hinder the development and advancement of GH_2 in the country are therefore highlighted in this section. Additionally, this section proposes strategic recommendations that can be adopted to propel this economy.

6.1. Potential barriers in advancing green hydrogen development

6.1.1. Water requirements

The production of GH_2 has synergies with water requirements. Freshwater feeding rate for electrolysis is $\sim$9 kgH_2O/kgH_2 (Newborough and Cooley 2021, Woods *et al* 2022). Although GH_2 plays a pivotal role in reducing the carbon footprint, it is essential to minimize its water footprint and prevent possible freshwater scarcity by exploring alternatives. Various reports have suggested seawater as an alternative. However, utilizing seawater entails purification processes such as demineralization or desalination, followed by cooling, which increases electricity consumption and water usage to approximately 9–25 kgH_2O/kgH_2. (Newborough and Cooley 2021, Woods *et al* 2022). For example, a reverse osmosis for desalination typically consumes 0.003 kWh/kgH_2O and from an economic perspective, studies have shown that reverse osmosis can add energy cost of USD 0.53–1.50 per m^3 of clean water produced. This equates to an overhead of 0.1% compared to the production of GH_2 utilizing freshwater (Newborough and Cooley 2021). This underlines the significant demand for both water and energy necessary for the GH_2 value chain.

Subsequently, on a global scale, over 85% of GH_2 projects planned are due to be developed in water-stressed regions (Matsubu 2022). Currently, South African GH_2 production projects have not been confirmed to utilize seawater, despite the country's coastal access. Therefore, policies, plans, and strategies for the GH_2 economy must incorporate water sustainability considerations and address its potential impact on potential water scarcity (Woods *et al* 2022). Although, Dyantyi-Gwanya *et al* (2025) asserts that South Africa should take advantage of its abundant water resources to maximize GH_2 production, Macingwane and Schönborn (2024), maintains that South Africa is water stressed country. As semi-arid country, GH_2 water demand may result in competition between GH_2 economy and existing water-dependent sectors such as agriculture, construction, and others (The Department of Trade Industry and Competition 2022b, Macingwane and Schönborn 2024). Moreover, in reference to the South African water supply, there is a need for feasibility studies to project the amount of freshwater and seawater necessary for the annual local and international supply of GH_2 (Beswick *et al* 2021). Furthermore, GH_2 production must be integrated into national freshwater demand and supply strategies to ensure the fair distribution of this limited resource. Importantly, integrated water resource management principles should account for the water needs of the GH_2 economy in their implementation. This emphasizes the importance of holistic and coordinated planning among various stakeholders to effectively manage water-energy synergies. Implementing these factors can enhance South Africa's economic competitiveness against countries such as Namibia. Namibia does not experience water stress and can leverage their water availability for GH_2 production through electrolysis, as noted by Gado *et al* (2024).

6.1.2. Increased demand for critical minerals

It is estimated that the mineral demand for global decarbonisation targets will need to quadruple and increase six-fold by 2040 and 2050 respectively (Tortell 2024). This increasing demand will certainly result in interdependencies between various countries (Berahab 2022), while being surged further by demands for batteries for electric vehicles, electricity storage and transmission infrastructure. The growing adoption of wind and solar power will drive increased demand for copper, silicon, and zinc (Tortell 2024). Similarly, the expansion of the GH_2 sector will increase the demand for platinum and iridium (which are minerals predominantly sourced from South Africa), particularly for manufacturing PEM electrolysers and fuel cells as stated by Dyantyi-Gwanya *et al* (2025). As demand rises, the long-term availability of these critical commodities, which are also essential to other industries such as automotive manufacturing, may be threatened. This could potentially lead to economic conflicts between sectors, thus highlighting the need for strategic regulatory frameworks to ensure a sustainable and conflict-free development of the green economy (Chakarvarty 2018).

Due to increased attention towards net zero ambitions, the demand for GH_2 has since increased by fivefold from 2021 and various nations have been announcing their plans to develop GH_2 economies. In January 2023, the Indian National Green Hydrogen Mission was approved. This mission included a plan to set up an electrolyser manufacturing capacity of 60–100 GW by 2030. Furthermore, in early 2022, the European Union announced to halt its dependency on the Russian fossil fuel denoting potential dependency on clean energy in addition to their GH_2 import targets of 10 Mt by 2030 (Kalt *et al* 2023, Parthenon 2023). Additionally, several PEM electrolyser manufacturers plan to expand their production capacity by up to 92 times between 2024 and 2030. South Africa could play a key role in supporting this growth by supplying critical minerals such as platinum and iridium (Parthenon 2023). Given the growing demand for these minerals, intensified competition in trade appears inevitable. These resources already occupy critical roles in both local and international markets, and their increasing indispensability is likely to amplify competitive pressures across various sectors.

Platinum has long been a cornerstone in various industries and its dominance is evident in the jewellery sector. In jewellery manufacturing, a typical alloy for castings consists of 90% platinum and 10% palladium. Contrary to other commodities, platinum jewellery is rarely discarded or recycled due to its high value and strong emotional attachment. In the automotive industry, platinum serves as a crucial catalytic agent in catalytic converters for internal combustion engine vehicles. As the production of fuel cell electric vehicles increases, its significance in the automotive sector is expected to increase even further. Platinum also plays a vital role in electronics and semiconductor manufacturing, where it is used in computer storage disks, thermocouples, sensors, capacitors, connectors, and electrical contacts (Wilburn and Bleiwas 2004). Iridium, although produced in smaller quantities, plays an equally critical role. Its global demand is highly volatile, with significant surges observed in response to technological trends. Its demand increased in 2010, and since then, iridium has become a dominant commodity in electronics, particularly for thin-film coatings and semiconductor production (Minke *et al* 2021).

The above-mentioned dynamics could escalate the race for access and control over these high-valued commodities, thus reshaping market landscapes, influencing geopolitical relations, and driving shifts in global trade policies. The question of how critical minerals can be sourced and supplied in a socially and environmentally responsible manner as the world transition towards sustainable economies remains unclear as heighted by Tortell (2024).

In 2020, the remaining PGMs reserves were sitting at 63 million tons with annual production of 0.226 million tons in the same year (Khan *et al* 2022). Interestingly, a research study has evaluated whether iridium may be a potential block in the large-scale production of PEM electrolysers; the study concluded that the current production rate of iridium cannot maintain an established market of PEM electrolysers. This can lead to supply shortages that could slow GH_2 implementation and increase the overall cost of GH_2 (Minke *et al* 2021, Tortell 2024).

South Africa can leverage on taking control of the GH_2 critical mineral value chain. Although this will need major investments and long-term planning in infrastructure, technology, and workforce development; lessons can be learned from China. China has succeeded in taking control over key stages of the critical minerals value chain by strategic industrial policy that has aggressively supported the development of its metal refining and processing sectors, thus resulting in market power and diversification of supply chains. As global geopolitical tensions rise due to critical minerals, various countries such as Canada and the European Union have also released strategies to strengthen mineral supply chain resilience and address potential supply chain risks as the world moves toward sustainable economies (Tortell 2024).

Platinum and iridium are essential catalysts in electrolysers and fuel cells, this makes them indispensable enablers across the GH_2 value chain. As global demands increase, South Africa, with its abundant PGMs, will be uniquely positioned to benefit. However, this also comes with responsibilities and potential challenges. To maximize opportunities while ensuring sustainability, South Africa must adopt strategic regulatory and policy frameworks and collaborate with stakeholders who support fair and equitable trade practices across Africa. This approach will help ensure that the extraction and use of these critical minerals are ethical and sustainable, thus preventing socio-economic inequalities and an unjust energy transition.

6.1.3. Energy security concerns

Foss (2022) defines energy security as the uninterrupted availability of energy sources coupled with affordable prices while ensuring reliable supply to meet current and future demands. However, researchers such as Chester (2010), characterize energy security as a polysemic concept that contains multiple dimensions that simultaneously depend on and evolve with the fundamental economic paradigms observed in energy markets (Chester 2010). Due to the energy transition which is not unique to South Africa, global energy policies ought to focus on four elements, namely, availability, accessibility, affordability and acceptability. However, Foss (2022) argues that these elements are not adequate to mitigate energy security concerns.

Fossil fuels remain a dominant energy source in South Africa. As the country strives to integrate renewable energy and GH_2 into its energy mix, it may encounter substantial energy development challenges. These include a growing population which drives higher energy demand, and the need to import GH_2 infrastructure and technologies to fulfil local clean energy requirements. The dependency on imports could expose South Africa to increased price volatility, leading to increased product costs, market fluctuations, rising inflation, and pressure from hard currency demands (Alemzero *et al* 2021). Therefore, integrating variable renewable energy and GH_2 infrastructure could pose energy security risks, particularly regarding the reliability of energy supply and the overall costs associated with the transition.

Green Hydrogen in South Africa will be dependent on solar and wind energy and these sources of energy are susceptible to the following challenges as reported by Azarpour *et al* (2013) and Smarte Anekwe *et al* (2024):

Solar energy:

(i) Photovoltaics (PVs) cells have moderately low efficiency, and this can result in a portion of solar radiation being lost as heat.
(ii) Conventional semiconductors used in current photocatalysts exhibit poor efficiency and stability, and this limits their practical applications.
(iii) The storage of energy by solar panels needs converting solar energy into electrical, thermal, or chemical energy. This process leads to a reduction of usable energy because a change of one energy to another depends on the conversion efficiency.
(iv) The recycling process of solar panels at the end of shelf life require additional energy.

Wind energy:

(i) Wind turbines require significantly large sizes of land and the unavailability of it thereof can pose challenges.
(ii) Wind turbines can cause noise pollution, especially if they are installed closer to human settlement.

While solar and wind energy are central to the country's GH_2 strategy, the challenges create potential vulnerabilities. Therefore, an approach that prioritizes technological innovation is crucial to addressing these challenges (Azarpour *et al* 2013, Smarte Anekwe *et al* 2024).

6.1.4. Financial implications

While financial limitations are often seen as challenges mainly faced by underdeveloped and developing nations, particularly in Africa, the global landscape reveals a different context. Globally, projects announced to produce low-carbon hydrogen (green and blue hydrogen), are estimated to reach a total output of 38 Mt by 2030. However, only 4% of this expected production has secured final investment decision, thus, revealing a gap between ambition and actionable financial commitment on a global scale (Hunt and Tilsted 2024). Hunt and Tilsted (2024) reported a typical example of a developed country facing GH_2 financial challenge in Denmark. This developed country announced GH_2 projects of 20 GW electrolysis capacity by 2030, meanwhile, only one project of 50 MW capacity made a final investment decision (Hunt and Tilsted 2024). The high cost of renewable energy is a major hindrance towards its swift implementation. For example, the cost of installing a large-scale solar power plant is approximately USD 2000 kW^{-1}, while the price of installing a new fossil fuel fired power plant is USD 1000 kW^{-1} (Smarte Anekwe *et al* 2024). Moreover, literature has reported the global estimated production of GH_2 to be at USD 3.6–10.30 kg^{-1} depending on the type of electrolyser used (Kazi *et al* 2021, Kumar and Lim 2022, Younas *et al* 2022), while that of grey and blue hydrogen is estimated at USD 1.66–1.84 kg^{-1} and USD 2.09–2.23 kg^{-1} respectively (Longden *et al* 2022).

In terms of country specific costs, a techno-economic analysis of GH_2 production done by Macingwane and Schönborn (2024) discovered that the cost of GH_2 production from wave energy in the Port of Ngqura (located in the eastern part of South Africa) is still relatively high, with an estimate of ZAR 96.07 kg^{-1}, equivalent to $\sim$USD 5 kg^{-1}. Therefore, investors may see electrolysis as a high-risk method of hydrogen production compared to grey and blue Hydrogen. In contrast, a comparative study done by Ayodele and Munda (2019) which investigated the capability and viability of GH_2 production from wind energy in South

Africa, discovered that the cost of GH_2 production is site and turbine dependent. The study further discovered that the lowest cost recorded at the most economical site ranges from USD 1.4 kg^{-1} using wind turbine model: Gamesa G128 to USD 39.55 kg^{-1} using wind turbine model: MICON. Therefore, it is critical to note that wind speed can significantly affect GH_2 production and its related viability. More importantly, the selected model of the wind turbine should match with the rated wind speed of the selected site (Ayodele and Munda 2019).

In addition, South Africa's electrical infrastructure is designed for fossil fuel-based power, meaning that, significant investment is required to develop new transmission infrastructure, especially for GH_2 energy storage systems (Smarte Anekwe *et al* 2024).

Another challenge in implementing GH_2 in South Africa is the nature of investments from international funders. The USD 11.6 billion allocated to the JETIP aims to accelerate the decarbonisation of the South African economy through clean electricity, electric vehicles, and green hydrogen. However, this investment has faced scrutiny over concerns about its viability, efficiency, effectiveness, and impact on energy security. Additionally, there are concerns about the lack of transparency, particularly regarding the funders' support for the privatization of South Africa's energy sector (Union of Justice 2023). The nature of the investments that will be used in addressing climate change includes concessional and market-rate loans, grants, commercial debt, and equity. While concessional loans are offered at lower interest rates and are more affordable to repay, they still need to be repaid eventually. This raises significant concerns about the long-term implications of this financial support (Union of Justice 2023, Bekele and Miller 2024). South Africa, although it only contributes about 4% of the global GHG emissions, it is one of the most climate vulnerable countries in Africa (Hunt and Tilsted 2024). Thus, it is ideal for the country to be eligible for grant-based financing, as non-grant-based financial risks could worsen the national debt, which is already a strain. Furthermore, loans raise ethical concerns, as they shift the burden of climate costs to a country that has contributed the least to the global climate crisis rank (Mwaniki and Freitas 2022). These financial mechanisms are conflicting the principles of the United Nations Framework Convention on Climate Change, which reiterates that resource transfer responsibilities lie with developed countries (Bekele and Miller 2024). Scholvin *et al* (2025), further contends that developing countries should avoid relying on instruments that could result in the burden of projects that may never deliver the anticipated returns. One of the questions that can be raised is 'What is stopping South Africa to mobilize its own GH_2 or climate finance?'. South Africa and many other African countries are affected by various barriers such as institutional capacity. Institutions often have weak systems, and they fall short of internal capacity to meet the minimum standards set by the international climate funds. They also lack (i) clear frameworks to access and manage climate funds, (ii) adequate technical expertise to create economically viable climate projects and programmes, (iii) suitable cross-sector coordination due to unclear mandates and (iv) sufficient data to support project development and negotiating capacities in addition to policy planning and climate change budgets. There is a lack of alignment between climate and development plans, limited data and analysis on domestic renewable energy costs, and an insufficient green taxonomy to guide private sector involvement (Mwaniki and Freitas 2022).

In addition to the factors mentioned, the COVID-19 pandemic had a significant economic impact on all sectors worldwide, especially in undeveloped and developing countries. It also strained government financial support for infrastructure projects, as unplanned funds were diverted to address the socio-economic effects of the pandemic. The severe economic repercussions of COVID-19 are still visible, and to make matters worse, net-zero construction materials are expensive (Akomea-Frimpong *et al* 2024). Therefore, mobilizing finances for GH_2 in South Africa requires establishment of financial institutions, deployment of innovative financial mechanisms, adoptions of cross-sector coordination, implementations of public–private partnerships (PPPs) and the development of rigorous and comprehensive policies to access grants effectively.

6.1.5. Environmental and biodiversity impacts

Understanding the environmental impacts associated with the GH_2 value chain is essential, as these impacts vary depending on the technologies used and their geographic location. As wind turbines may require large land areas, they have a lifespan of 20–25 years, and they generate minimal GHG emissions during their construction. However, during operation, wind turbines can create shadow flicker from sunlight, which may disrupt nearby residential areas. Wind turbines also pose a threat to the livelihood of birds as they are likely to crash into stationary and moving blades, towers and nacelles. This is likely to occur if the turbines are installed on slopes or near bird migration routes. Moreover, some birds, particularly bats, can be affected by increased turbine pressure, thus, causing internal haemorrhaging (Carlson *et al* 2023).

Issues around impacts from wind turbines installed offshore are often not addressed. Foundation components of turbines can introduce foreign substances into the seabed. This can damage benthic plants and block the sunlight from the seabed. Furthermore, offshore wind farms can create artificial reefs which can significantly change the biodiversity and the noise coming from the turbines can negatively impact marine life. Additionally, maintenance activities can further lead to sea contamination from waste and oil spillages (Nazir *et al* 2020).

During PV cells manufacturing, installation, and recycling processes, chemicals used may be released in the air, surface water, and groundwater. This leads to air pollution and potential harm to aquatic biodiversity. Carlson *et al* (2023), emphasized on a study done to analyse chemical data from the US Environmental Protection Agency (EPA's) Toxics Release Inventory System for six solar cell manufacturers. This study indicated that most chemicals used in the aforementioned processes are not released in reportable quantities. However, certain PV-related chemicals contributing to air pollution have been detected as stack emissions and fugitive air emissions (Carlson *et al* 2023). Moreover, PV panels installation requires significant amount of land, thus reducing cultivable lands and if animals (particularly wildlife) are removed from their habitat to create land for panels, their ecosystem will be disrupted (Rahman *et al* 2022). It is therefore critical to adopt sustainable practices aimed at minimizing the environmental impacts of clean energy technologies. Hou *et al* (2015) suggests optimized placement of wind turbines to reduce land and wildlife disruption while Tandel *et al* (2021) urges for exploration of bladeless turbine designs to mitigate bird and bat collisions. Furthermore, Sathyanarayanan *et al* (2024) emphasizes on the development of eco-friendly materials for solar panels, while Zhdaneev and Aleshkevich (2024) suggests implementation of efficient recycling methods for renewable energy components (Hou *et al* 2015, Tandel *et al* 2021, Sathyanarayanan *et al* 2024, Zhdaneev and Aleshkevich 2024). In addition to the above-mentioned impacts; the extraction and processing of minerals that are critical to the GH_2 value chain have potential to also pose adverse environmental impacts such as pollution, habitat destruction, and resource depletion, thus worsening Africa's fragility of climate change and thwarting decarbonisation efforts (Berahab 2022). Mining activities such as drilling, blasting, crushing and grinding, loading, hauling, and beneficiation have a variety of effects on the environment by causing drastic alterations to landscapes and geological structures, loss of vegetation, and disruptions to ecosystems. Mining activities also release GHG such as carbon dioxide, methane, and nitrous oxide. Therefore, there remains a need to establish a balanced synergy between mining activities of critical minerals, environmental protection, and sustainable mining development as critical mineral demand grows (Sonter *et al* 2020, Onifade *et al* 2024).

6.2. Strategic recommendations for accelerating green hydrogen adoption

6.2.1. Technological advancement and cost reduction through research and development (R&D)

South Africa can significantly benefit by prioritizing R&D as one of the core elements in the advancement of GH_2 economy, especially since largescale producing of GH_2 is not yet commercially viable. By taking this approach, the country can not only accelerate the development of advanced technologies but also explore diverse methodologies for GH_2 production and applications. These advancements could substantially lower the capital costs of GH_2 across the value chain, thus enhancing its competitiveness and long-term sustainability. For example, Cammeraat *et al* (2022) reported that approximately 60% of the electrolyser cost reduction could result from R&D as well as economies of scale and learning-by-doing (Cammeraat *et al* 2022). As a country that is positioned to leverage on critical minerals such as platinum and iridium for PEM manufacturing; the strengthening of R&D efforts in technological innovation is key. Berahab (2022) further reiterates that this approach can ensure the efficient use of minerals and their potential substitutes, enhances national supply chain capabilities, and accelerate innovations that can also promote the recycling of end-of-life electrolysers. Consequently, it helps reduce the negative environmental impact of critical mineral extraction (Berahab 2022).

The importance of R&D initiatives is evident in the United States, a developed country that has made significant strides in advancing its GH_2 energy strategy. The 2014 Comprehensive Energy Strategy emphasized investments in R&D, and in 2020, the US Department of Energy reaffirmed its commitment to hydrogen energy research, with more focus on production, transportation, storage, and utilization. Furthermore, in 2021, the US allocated USD 8 billion to establish a national R&D centre, regional hubs, and infrastructure development (Islam *et al* 2024). Pursuing similar initiatives in South Africa coupled with strategic engagements across factors such as policy implementations can aid in realizing sustainable growth across the GH_2 value chain (Smarte Anekwe *et al* 2024).

6.2.2. Investments and financial mechanisms

Climate finance is a critical component in addressing both climate change and sustainable development objectives. The expansion of investment in the development of GH_2 in South Africa needs to gain significant momentum to aid in meeting decarbonisation targets, particularly within hard to abate sectors. As previously highlighted, investments from international partners pertaining to the energy transition in South Africa primarily consist of loans. However, various financial investments towards the GH_2 such as the KfW Development Bank-Industrial Development Corporation (IDC) Programme, Power-to-X (PtX)

Development Fund and the SA-H_2 Fund have been announced (KfW 2023, The Presidency Republic of South Africa 2023, Creamer 2024). South Africa should be cautious of loan-investing entities that may impose unfavourable derisking measures, potentially altering the dynamics between the country and private investors, reducing profits, and shifting risks from investors to the government. In this context, derisking refers to strategies investors use to minimize their risk exposure, usually by adjusting terms and conditions in ways that transfer financial burdens onto the borrowing country (Taghizadeh-Hesary *et al* 2022, Hunt and Tilsted 2024).

Green hydrogen funds should have a variety of revenue streams in the medium to long term to ensure scalability, replicability and sustainability of the project. This can be achieved by attracting private sector investment, however, the national government ought to implement comprehensive and actionable GH_2 policy and regulatory frameworks that create market-based mechanisms to incentivise private businesses and allow private investments to meet the required rate of return (Shipalana 2020). As the world embraces energy transition, innovative finance approaches such as green banks and ethical banks are now being explored. Ethical banks are financial institutions committed to sustainable and responsible investments, while green banks are public purpose financial entities designed to drive green investments and meet local clean energy financial needs. As highlighted by Shipalana (2020), Morocco and South Africa have expressed interest in establishing green banks. This highlights a significant gap in the financial sector, a growing recognition of the role of green banks in promoting sustainable investments, and their potential to accelerate localized solutions to bridge the climate investment shortfall (Shipalana 2020).

Local exploration of green banking has been demonstrated. Amongst other banks that have explored innovative climate finance solutions, Nedbank has shown its responsibility in emphasizing its leadership in renewable energy funding in South Africa. The bank introduced the first renewable green bond on the green segment of the Johannesburg Stock Exchange. The investment proceeds will enable the bank to deliver financial support to solar and wind renewable energy projects with the aim to create long-term sustainable solutions for the country (Shipalana 2020, Elsner and Neumann 2023). Nedbank has actively supported the country by allocating 3.9% of its advances to renewables in 2019 and offered absolute funding under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) and many other environmental initiatives. Additionally, through a tailored Greenbacks charity program, Nedbank has created an opportunity for its clients to support environmental initiatives across the country (Elsner and Neumann 2023).

However, there remains a need for this innovative financial mechanism that are tailored to penetrate the GH_2 which remains with financial challenges in securing adequate funding, particularly across the value chain for large scale projects. This can promise chance to overcome GH_2 financial challenges across the board. In addition to this, Bekele and Miller (2024) further highlighted that investments from the Global North in particular, should reflect on acknowledging their historical responsibilities and consider ensuring a net positive transfer of investments to climate action, not only in South Africa, but the African continent (Bekele and Miller 2024). Reforming the global climate financial architecture towards more innovative approaches is imperative as it can lead to a 'Just' and equitable energy transition.

6.2.3. PPPs

According to the South African law, a PPP is defined as a contractual agreement between the government and a private entity, where the following applies (Nel 2018):

(i) The private entity undertakes an institutional function and/or utilizes governments assets according to specified outputs.
(ii) Significant project risks, including financial, technical, and operational risks, are transferred to the private entity.
(iii) The private entity is compensated through payments from government budgets and/or user fees.

Soumalevris (2023) outlines that private entities that often pursue PPPs model usually consist of a consortium of private companies such as construction firms, banks, management experts, consultants and accountants, amongst others. PPPs within the South African GH_2 sector can particularly strengthen the sector's market mechanisms. This is because the private sector is widely known for its innovation, capacity to provide capital, better governance, and extensive technical expertise (Awuku *et al* 2021, Soumalevris 2023).

The South African GH_2 sector can benefit from several advantages of PPPs. These advantages include accelerated infrastructure development (Awuku *et al* 2021), cost and risk reduction (Udeagha and Ngepah 2023), and availability of advanced technology and innovation that can improve the efficiency of GH_2 projects (Othman and Khallaf 2023). Moreover, Adelakun *et al* (2024) further adds that PPPs are critical in gauging effective financial viability and sustainability, stakeholder engagement and capacity building, financial institutions, regulatory complexity and skills development (Adelakun *et al* 2024).

To date, the South African government has shown initiative in pursuing PPPs through REIPPPP (Nel 2015). The REIPPPP was established by the South African government as a strategic initiative to achieve a diversified energy mix and broaden energy accessibility. The program seeks to align with the policy objectives outlined in the National Development Plan, expand energy infrastructure, promote sustainable development, ensure equitable energy access across the country, and attract private sector participation and investments by facilitating the procurement of energy from independent power producers (IPPs). This is in hopes to support the government to meet its decarbonisation targets, and increase employment and growth rates (Nel 2015, 2018). Since the inception of the REIPPPP in 2011, over a 100 IPPs have adopted renewable energy, diesel and battery technologies (South Africa Government News Agency 2024). Although PPPs play a significant role in solar and wind energy, there is still an opportunity for more involvement in the GH_2 value chain, particularly in production, transmission and distribution, storage, and refuelling processes.

The PPP model within the energy sector has shown many successes across various parts of the African continent. For example, Cameroon has The Kribi Gas-fired Plant comprising of a 216 MW gas fired power plant and a 100 km long 225 kV transmission line which was built through the collaboration between the Cameroon government and AES corporation. Another success from the PPP model in the energy sector is demonstrated by Mozambique with the 107.5 MW Ressano Garcia Gas Fired Power Plant, situated on the Mozambique/South African border and owned by Aggreko, along with its joint-venture partner Shanduka Group. Moreover, the project is the result of a Power Purchase Agreement that Aggreko have signed with Electricidade de Moçambique and Eskom (Aitken 2014).

There are lessons that can be taken from existing national PPPs that were formed in other sectors. These lessons demonstrated successful blueprints and re-emphasized their importance in driving the national economy. Udeagha and Ngepah (2023) also emphasized that local municipalities have been increasingly showing interest in PPPs to increase operational efficiency and access to capital. Furthermore, the success of a PPP model in South Africa has been demonstrated by a partnership between Gauteng Provincial Government and Bombela Concession Company (comprising of shareholders such as Murray & Roberts Limited, Strategic Partners Group, Bombardier UK, Bouygues Travaux Publics, The J&J Group, and Absa Capital). This PPP entity brought about Gautrain through a build, operate and transfer model (Fombad 2015, Railway Technology 2020). This project has significantly enhanced the transportation system within the Gauteng province, thus, illustrating the potential benefits of PPPs that could be leveraged in the GH_2 sector (Udeagha and Ngepah 2023).

Soumalevris (2023) further stresses that PPPs play a key role in decarbonizing economies while leveraging private companies' extensive experience in the renewable energy sector. In the long term, this can improve national budgets, allowing funds to be allocated to essential public services such as healthcare and education. Additionally, these budgets can support further infrastructure projects, maximize socio-economic impact and demonstrate the model's value for money by generating a net positive gain for society. Private investors often prioritize higher initial capital expenditure, focusing on quality and sustainability. This approach reduces long term operational and maintenance costs over the project's lifespan. In contrast, government procurement typically follows a bid process that favours the lowest-cost contractors. While this is cost effective in the short term, this approach often compromises long term quality and sustainability, thus leading to higher future maintenance costs and reduced project longevity (Soumalevris 2023). Other advantages of the PPP model include the efficiency of economies of scale, as private sectors are more innovative and able to design, construct and operate technically complex and capital-intensive projects more competently. Additionally, private sectors have more transparency and accountability, while public sectors have a record of failed accountability, particularly to the public (Othman and Khallaf 2022, Soumalevris 2023). Although there lies potential in PPPs models, Agyekum (2024) raises concerns relating to corruption in the African energy sector and government departments, where corruption is active in different levels of development of renewable energy. The author therefore advocates for developers and operators, in this case private entities, to manage such ordeals (Agyekum 2024). However, the PPP model is a promising alternative for promoting productive collaborations and implementations, while integrating innovative clean energy solutions, enhancing financial mechanisms, and accelerating the transition to an environmentally friendly economy.

6.2.4. Implementation of government policy and regulatory support

The implementation of comprehensive policies and regulatory support is a key driver in accelerating the GH_2 sector. Currently, South Africa lacks specific comprehensive policies for GH_2. However, in 2021, the nation released the Hydrogen Society Roadmap, which outlines national targets for the GH_2 value chain from 2021 to 2040 (Department of Science and Innovation 2021). South Africa also released the Green Hydrogen commercialisation strategy 2022, which highlights the GH_2 strategic design principles, market dynamics, natural resources, socio-economic development, and the importance of equitable and just energy transition. This commercialisation strategy also identified the following elements that need further expansion; financial support mechanisms, regulatory measures and policies, R&D and direct national investments (The Department of Trade Industry and Competition 2022a). Additionally, the JET-IP 2023–2027 highlighted various initiatives that are aimed to catalyse the implementation of GH_2 technologies and manufacturing of fuel cells and electrolysers, while addressing critical stakeholder engagement, putting emphasis on the importance of trade relationships and underlining the national reduction of unemployment though skills development (The Presidency Republic of South Africa 2023).

Lessons can be learned from developed countries such as the USA, where GH_2 saw substantial momentum in 2021. This was following the Infrastructure Investment and Jobs Act as well as the USD 62 billion investment to the US Department of Energy, in addition to the USD 9.5 billion specifically dedicated for GH_2 hydrogen initiatives (Alam *et al* 2024). Collaborative efforts with various regulatory bodies such as the Pipeline and Hazardous Materials Safety Administration, the EPA, the Federal Energy Regulatory Commission and the Occupational Safety and Health Administration are rigorously pursued to support GH_2 initiatives. Furthermore, the US Department of Energy have initiated tax incentives and subsidies through programs such as the Tax Credits for GH_2 producers to improve the commercial viability of producing clean hydrogen and encourage investments in hydrogen technologies (Bade *et al* 2024, Bade and Tomomewo 2024).

The USA launched the Hydrogen Energy Earthshot in 2021 to accelerate a transformative shift in the GH_2 economy. This initiative aims to stimulate private sector investments, drive development across the hydrogen supply chain, and significantly reduce the cost of GH_2 to USD 2 per kg by 2026 and USD 1 per kg by 2031. Beyond cost reduction, the Hydrogen Energy Earthshot also focuses on improving durability, recyclability, and optimizing the GH_2 supply chain. Furthermore, in June 2023, the country released the National Clean Hydrogen Strategy and Roadmap, which provides a comprehensive framework to accelerate GH_2 implementation and expand its use across various sectors. This supports ambitious climate goals, economic growth, and the creation of well-paying jobs (Alam *et al* 2024).

Drawing from the above-mentioned, it is critical that South Africa implements initiatives and regulatory frameworks that are specific to GH_2. These policies and regulatory frameworks must be integrative, actionable and strategically prioritize the afore-mentioned recommendations that will aid in propelling (i) technological processes, (ii) innovative financial mechanisms, (iii) PPPs and industry collaboration that will assist in leveraging expertise and resources across various sectors. Moreso, these policies and regulatory frameworks must (iv) promote community engagement and social license to operate, (v) support natural resource utilization that ensures efficient and ethical use of critical minerals (vi) promote sustainable job creation and (vii) endorse GH_2 cost reduction and incentives.

7. Conclusion

Green hydrogen holds significant potential for decarbonizing hard-to-abate sectors in South Africa. It also serves as an effective energy storage solution and address the intermittent nature of renewable energy sources while positively impacting the country's socio-economic landscape. Despite its abundant natural resources, South Africa faces financial constraints. Given the country's high unemployment rate, policymakers ought to not only leverage GH_2 to meet decarbonisation targets and generate financial gains but also prioritize its role in strengthening the local economy, creating jobs, and addressing energy security challenges. While the current GH_2 landscape in South Africa highlights its potential, this paper identified that the country must implement clear and coherent GH_2-specific policies and regulatory frameworks to tackle challenges such as water requirements, rising demand for critical minerals, energy security concerns, financial constraints, unemployment, and environmental and biodiversity impacts. To accelerate GH_2 economy development, the paper brought forth key recommendations which include advancing technology, reducing costs through R&D, enhancing investment and financial mechanisms, pursuing PPPs, and implementing strong government policies and regulatory support. Actioning the above mentioned can aid in realizing a socio-economic beneficial GH_2 economy.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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