# Prospects of Solar Driven -Water Electrolysis for Hydrogen Production in South Africa: A Mini-Review

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***Abstract***— The global interest in green hydrogen as a sustainable energy for socio-economic growth and development is gaining much attention. South Africa, being recognized as a water-stressed country with highly industrially generated wastewater, also depends mostly on coal-powered plants, thus being a huge emitter of greenhouse gases. Addressing these challenges requires a technological solution to transform the country's carbon-based economy into a green economy with a sustainable environment. However, the development of a green economy has an intricate connection to decarbonization with different routes of energy production and wastewater treatment techniques. In this study, a comprehensive review of hydrogen production routes was conducted. The development of hydrogen hubs in South Africa was highlighted. The production of green hydrogen via renewable resources was found to be economically and sustainably viable. Therefore, the prospects of solar-driven-wastewater electrolysis as a hydrogen technological solution to the current South African energy sector to drive the hydrogen economy come in handy.

***Keywords***— Decarbonization; fossil fuels; green hydrogen; solar energy; electrolysis

## I. INTRODUCTION

On the path to a sustainable future, energy security and climate change mitigation represent two of the most pressing challenges [1]. Notwithstanding, the high demand for carbon-based fuels (fossil, coal, natural gas, and oil) pose an unfavourable risk to human health and the environment with greenhouse (GHG) gas emission [2, 3]. Of interest, carbon-based fuels provide 85% of global energy needs and emit about 36 billion tons of $CO_2$ annually [4]. Global energy consumption is projected to increase by 28% from 575 quadrillion Btu in 2015 to 736 quadrillion Btu in 2040, threatening climate change efforts to mitigate it [5]. Therefore, exploring technologies to produce alternative carbon-based fuels for decarbonization of the atmosphere [6], comes in handy. Consequently, the production of hydrogen from renewable sources has great potential to accelerate a sustainable circular economy and reduction of carbon footprints.

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Conventionally, hydrogen is usually produced through thermochemical techniques that use fossil fuels such as hydrocarbon reforming, coal gasification, hydrocarbon pyrolysis, and plasma reforming process. Meanwhile, renewable energy sources (20-21%) are underutilized as compared to fossil fuels (79–80%) [7]. Based on this, multiple research efforts have been centred on creating new technologies for renewable energy sources as a replacement for fossil fuels. Aside fossil fuel resources, hydrogen can be obtained from biomass, and water. However, to produce hydrogen sustainably, the aforementioned natural resources can be used along with potentially available renewable energy (solar, wind, sea wave, etc.) [8].

South Africa has been reported among the world’s worst polluter countries due to its industrial activities that continue to rely on coal-power generation with a high carbon footprint. Notwithstanding, South Africa is endowed with abundant natural resources such as wind, sun, and vast coastlines (seawave), which can be utilised for hydrogen production. However, to the best of our knowledge hydrogen technological exploration and product usage is still undervalued.

To curb this, the South African Government together with its Science and Innovation are championing a national goal for hydrogen hubs towards meeting the Paris Agreement of limiting global warming in the 21st century [9]. Nevertheless, the potential of the high sun irradiance in the region favours green hydrogen production using solar-driven electrolysis. Thus, the use of renewable energy sources (solar) will compensate for the cost of energy/electricity required for electrolysis. Herein, exploring green hydrogen production via wastewater-driven solar electrolysis comes in handy for decarbonisation and meeting the energy needs of the country [10]. However, its sustainability depends on the cleanliness of the hydrogen production pathway and the source of energy feedstock used during the process.

Therefore, this study presents a review of hydrogen production from non-carbonaceous technologies and renewable energy resources. The associated challenges and potential solutions for achieving a sustainable hydrogen economy in South Africa.

https://doi.org/10.17758/IICBE5.C1123023

## II. An Overview of Hydrogen Production Publications

This section details how the literature review was conducted in terms of searching, collecting, and compiling knowledge gap findings associated with the challenges and prospects of producing hydrogen from renewable energy sources in South Africa. The data for this study were obtained from peer-reviewed published journals by using the Google Scholar search engines, Scopus and the Web of Science Core Collection database. The search for literature under the theme of this study was done with appropriate keywords. Some of these keywords included "$CO_2$ emission", "decarbonization", "fossil fuels", "green hydrogen", "solar energy", electrolysis", "non-carbonaceous technologies" and renewable energy". The document type was defined concerning peer-reviewed journal articles ("research article" and "review article") excluding books, book chapters and conference papers. To avoid translation difficulty and easily read of relevant information from the article, the English language was selected. However, due to the rapid development of hydrogen production in recent decades, the data span for this study was set from 2010 to 2022 with a total of 34291 publications obtained as of June 25, 2023. And most of the literature searched were from the multidisciplinary area of energy, economics, sustainability, engineering, chemistry, water, social welfare, advanced technology, environmental and material science. Notwithstanding most of the published hydrogen production-related articles were from advanced countries, whereas a considerable BRICS (Brazil, Russia, India, China, and South Africa) countries/regions showed narrow active research in the field of hydrogen economy (Figure 1). This resulted in a total of 333 published articles, where the order of sequence was China (228) >India (61)>South Africa (16)>Brazil (15)>Russia (13). This could be attributed to the fact that China has paid much attention to studying the theory and practice with a detailed developmental plan towards the hydrogen economy transformation. Also, the collaboration between China, Japan, the USA, and other institutions at the global level was found to be more frequent, than the BRICS counterparts, especially with South Africa. This exercise identified research progress on hydrogen production technologies, which necessitate a scientific basis to improve South Africa's hydrogen economy research. The number of articles (16) published on this topic within the scientific space over the decade by South African institutions was so low. South African institutions with publications affiliated with this topic identified were the University of Pretoria (4), University of Johannesburg (3), Stellenbosch University (2), Tshwane University of Technology (2), University of KwaZulu Natal (2), Council for Scientific Industrial Research (CSIR, 2) and University of Witwatersrand (1). This requires urgent attention to the hydrogen policy roadmap to bridge the gap between research and industrial activities.

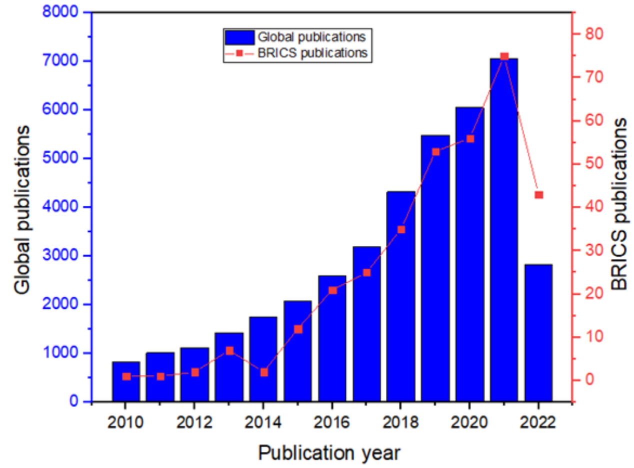


Fig.1 Annual hydrogen publication trend during the period of 2010-2022

### A. Research themes and keyword findings

There were a total of 1500 keywords related to green hydrogen production research extracted from the published article documents. A series of data management processes was carried out to make the data more reasonable. Also, by limiting the keywords occurrence to 5 times with a strong connection to the subject under study, about 65 keywords were obtained. Similar keywords such as "$CO_2$ emission", "decarbonization", "fossil fuels", "green hydrogen", "solar energy", electrolysis", "non-carbonaceous technologies" and renewable energy" still emerged. As shown in Figure 2 , there are 4 main distinct clusters from the co-occurrence network. The different clusters were shown by different colours, whereas the same colours indicate the same clusters. Cluster 1 (red colour) was the most frequently mentioned keyword in research related to green hydrogen. Notwithstanding the search term "hydrogen production" was strongly related with "water electrolysis", "water splitting", electrolysis, electrocatalysis and the rest represented the largest cluster. Cluster 2 (blue colour) relatively represented the production of green hydrogen via biological processes. It was deduced that using "fuel cells", "fossil fuels", "cationic and anionic systems", ammonia and other "energy" systems can enhance the production of green hydrogen. Cluster 3 (green colour) showed the resources by which biohydrogen can be produced, whereby "water", formed the central component. Also, the degradation of organic substrates to generate hydrogen was identified. Cluster 4 (yellow colour) denoted that production from renewable resources including "solar energy" can enhance photocatalytic processes to produce green hydrogen. Aside, the efficiency of water-splitting process to produce green hydrogen, it is also energy-intensify. Whereas utilising electricity or power generated from coal or fossil fuels are not economically and environmentally viable. Moreso, photocatalytic decomposition of water to hydrogen is also gaining research attention. In addition, biohydrogen and green hydrogen powered by hybridized solar, wind, and hydropower require long term implementation.

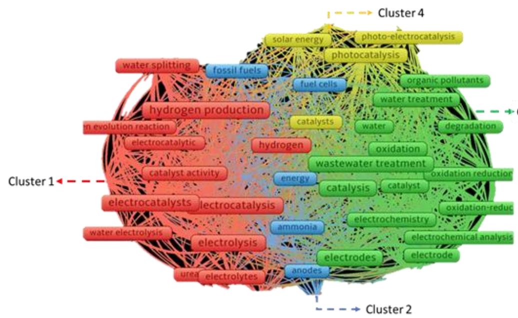


Fig 2 Network occurrence of frequently used keywords related to green hydrogen production.

### B. *State of green hydrogen projects*

In the current energy trajectory, the debate on green hydrogen energy dominating other energy sources in the foreseeable future is still ongoing. In this context, the number of countries with policies that directly encourage investment in hydrogen technologies is on the rise. For example, Australia, China, India, South Africa, Indonesia, Japan and other Western developed countries have commercialised hydrogen projects towards zero carbon emissions [11]. Also using hydrogen for energy production and industrial applications has drawn the attention of the European Union to increase its production to curb carbon emissions by 2050. Green hydrogen is a viable fuel for sustainable development and energy transition due to its ability to be created from water and renewable energy sources without greenhouse gas emissions through electrolysis. Globally, attempts are underway to manufacture green hydrogen from renewable energy sources like wind and solar. From the survey, Table 1 presents information on the implementation and development of green hydrogen infrastructure.

TABLE 1 GREEN HYDROGEN ONGOING PROJECTS AND THEIR LOCATION

| Project location | Description | Remarks |
| --- | --- | --- |
| Australia (Queensland) | 3000 MW green hydrogen electrolysis facility project is being designed for the export of green hydrogen | Hydropower generation of electricity |
| Canada (Quebec) | An electrolysis installation of 88 MW capacity to produce 11 100 tonnes of green hydrogen per year | Renewable technology in the generation of electricity |
| Democratic Republic of Congo (DRC) | Kamoa Copper Mine is powered by hydropower installation of 240 MW capacity to produce 600 000 tonnes per year. | Hydropower generation of electricity |
| Germany | A green hydrogen project coupled with an electrolysis plant of 100 MW capacity commission in 2025 | Renewable technology in the generation of electricity (Wind and solar) |
| North Wales (UK) | A hydrogen modular reactor of 3,000 MW using wind to produce 3 million kg of green hydrogen by 2027 | Renewable technology in the generation of electricity (wind) |
| South Africa | *Anglo-American Mogalakwena mine developing a pilot plant of 3.5 MW to produce 1 ton /day of green hydrogen to power the fuel cells for running large haul trucks.<br>*Sasolburg green hydrogen 2 kt $H_2$/year<br>*Nelson Mandela Bay Hive for green ammonia /hydrogen production of 140 kt $H_2$/year capacity.<br>* Secunda SAF and Boegoebaa green hydrogen by Sasol of capacity 8 kt $H_2$/year and 400 kt $H_2$/year respectively. | Renewable technology in the generation of electricity (solar PV) |
| South Korea | A liquefied hydrogen plant constructed for urban/domestic to supply 30,000 tonnes/year | Renewable energy source for electricity |
| Sweden | A hydrogen storage facility of 100 $m^3$ installed at a rock cavern below 30 m ground to be commissioned by 2024 | Renewable energy source for electricity |
| Switzerland | A hydropower plant on the Rhine River of 2.5 MW in capacity to produce 350 tonnes/ year of green hydrogen | Hydropower generation of electricity |

## III. HYDROGEN PRODUCTION ROUTES

The production of hydrogen presents a widely available energy source to replace fossil fuels in transportation, industrial, residential, and commercial sectors. Thus, an economy based on hydrogen has a prospective solution to environmental issues, natural resource depletion, and socioeconomic demands of population growth [2, 12]. Also, the production, transportation, storage, conversion, and usage of hydrogen for all fundamental aspects of the economy has a formidable advantage over the fossil fuel economy. Consequently, it is challenging for decision-makers to identify promising innovations and advantageous technology [13]. Herein, reforming, gasification, partial oxidation, water electrolysis, and dark fermentation [13-15], are identified among the conventional technologies that use fossil fuels and renewable resources. Hydrogen can be derived in molecular form from various sources, including fossil fuels, biomass, and water [14, 15]. To extract hydrogen from these sources, excess readily available energy is required. However, the viability of hydrogen production is related to the environmental impact of the production route and the amount of energy required for the process. Therefore, harnessing the potential of renewable energies (solar, wind, ocean waves, etc.) for hydrogen production technologies could allow sustainable production [16, 17]. Nevertheless, hydrogen energy systems can be simply implemented by modifying current transportation and fossil fuel energy systems, thereby reducing global carbon emissions.

In this context, green hydrogen can be produced from water or bio-based compounds. Despite the undeniable environmental benefit of using sustainable hydrogen for energy production, energy demand is inversely correlated with economic growth [18, 19]. Subsequently, the type of hydrogen production technologies can be determined by the type of basic material used, such as renewable resources (water and biomass) or fossil fuel. For instance, producing hydrogen from renewable energy sources is preferable because it reduces carbon emissions and is therefore considered environmentally benign or green. Grey and blue hydrogen can also be produced from non-renewable energy sources, such as fossil fuel and natural gas. The grey method releases carbon dioxide into the atmosphere, whereas the blue method captures it, making it more expensive. Hydrogen produced from fossil fuels using conventional technologies with hydrocarbon reforming and pyrolysis have been the most prevalent[13]. Since production costs are highly correlated with fuel prices at acceptable levels, fossil fuels continue to dominate the global hydrogen market. However, 77% of South Africa's energy needs are met by coal, which is the country’s primary energy source [20]. High $CO_2$ emissions and high carbon content are the most significant issues associated with hydrogen production through coal gasification [21]. Therefore, it is necessary to combine coal gasification with carbon capture-based technologies. Moreover, independent electricity generation from solar and wind power can potentially improve the hydrogen production route in South Africa.

## IV. Green hydrogen production via water electrolysis

Water electrolysis represents the low-cost, clean, sustainable, and most efficient method of generating hydrogen and oxygen via the cathodic hydrogen and anodic oxygen evolution reactions[22]. In electrolysis, the water molecule serves as the reactant, which dissociates into $H_2$ and oxygen by applying expensive electricity that is generally derived from non-renewable sources[22, 23]. This makes it expensive to operate and accounts for only 4% of the world's $H_2$ production. Water electrolysis technologies have been continuously developed and implemented in industrial settings since the 18th century. Throughout this trajectory, various trends have influenced their development, resulting in a roughly five-generational phase. Figure 3 shows challenges, technological advances, and the significance of each water electrolysis generation. Despite the economic and energy barriers, water electrolysis is gaining research attention [22, 24]. Based on the type of electrolyte and ion-based agent ($OH^-$, $H^+$, $O^{2-}$), this is classified as (i) Alkaline water electrolysis (AWE), (ii) Proton-exchange membrane (PEM) water electrolysis and (iii) Solid oxide electrolysis (SOE). The fundamental mechanism of water electrolysis is expressed in equations (1-3). Approximately 9 litres of water is required to produce 1 kg of hydrogen and 8 kg of oxygen via electrolysis [22]. South Africa is in an ideal position to produce green hydrogen water electrolysis because of the abundance of industrial wastewater and rivers (for example, the Umgeni River) as well as the coastline of the Indian Ocean. Therefore, exploring water electrolysis coupled with energy sources (such as solar and wind energy) can potentially improve the generation of clean hydrogen, while simultaneously reducing costs [25].

$$Anode:\ H_2O \rightarrow 2H_2 + {}^{1}/_{2}\,O_2 + 2e^- \qquad (1)$$

$$Cathode:\ 2H^+ + 2e^- \rightarrow H_2 \qquad (2)$$

$$Overall\ process:\ H_2O + energy \rightarrow H_{2(g)} + {}^{1}/_{2}\,O_{2(g)} \qquad (3)$$

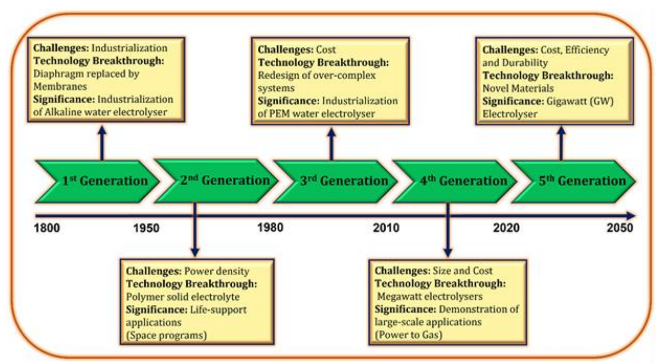


Fig.3 Schematic of water electrolysis phase generation [14]

## V. Challenges and prospects of hydrogen production in South Africa

The green hydrogen economy provides green energy with a considerable environmental impact compared to current fossil-based energies. However, South Africa’s research into green hydrogen energy is still in its early stages. Also, the potential benefits of hydrogen to South Africa’s society, businesses, and the government are yet to be understood, this necessitates studies on the socioeconomic effects of green hydrogen [26]. Therefore, national education campaigns are needed across all industries that are major stakeholders in hydrogen production, including the energy, transportation, academic, and industrial sectors. It is essential to inform the public about the function and viability of hydrogen during decarbonization. In addition, initiatives must be taken to inform qualified individuals with technical backgrounds about the job prospects of the hydrogen economy [26]. Despite the enormous promise of the hydrogen economy, there are still obstacles to be solved, such as the high cost of manufacturing, storage, distribution infrastructure, and safety concerns [24, 27]. However, governments, businesses, and academic institutions are making significant investments in hydrogen technology and striving to get over these challenges [28]. South Africa is ambitious to reduce its carbon footprint and secure the country’s energy future. Therefore, three centres of competence have been established to harness the hydrogen market of South Africa. These include (i) HySA Catalysis at the University of Cape Town and South Africa Mineral Research Council (MINTEK) to develop catalysts and catalytic devices for fuel cells and hydrogen production. (ii) HySA Infrastructure at the North-West University (NWU) and Council for Scientific and Industrial Research (CSIR) to develop technologies for hydrogen production, storage, and distribution. (iii) HySA Systems at the University of the Western Cape to develop systems integration and technology validation. Consequentially, the concern about hydrogen production, storage, distribution, and safety issues must be addressed [27]. Herein, governments, industries, and academic institutions are investing heavily in hydrogen technology to overcome these obstacles. In the meantime, the infrastructure needed to export hydrogen is comparable to that of existing natural gas networks. Therefore, South Africa could utilize its existing port infrastructure to support exports of hydrogen. Similarly, natural gas fields will offer an alternative solution in the form of hydrogen storage [29]. Hydrogen is presently being tested in the United Kingdom, where it is produced on land and piped into depleted gas fields for storage until needed [14].

South Africa can position itself as a nation that can produce renewable hydrogen on a large scale and at competitive prices, thereby generating an export market that will lead to economic development and energy independence. Notwithstanding, hydrogen can be produced and consumed widely in industrial processes. Sasol’s FischerTropsch (FT) technique and technical expertise provide South Africa with an edge in hydrogen-based liquid fuel manufacturing [26]. Nevertheless, the development of the hydrogen sector is hindered by technological obstacles, resulting in South Africa's prototyping deficit. Even if some hydrogen-related technologies are already used, they need to be made more cost-effective. This requires consistent funding for research and development. Currently, research and development in the hydrogen industry is intermittently supported by short-term financial assistance programs, resulting in limited private sector investment. Therefore, South Africa's hydrogen sector needs long-term support to grow. Drastic adjustments in the South African energy sector are required immediately with long-term objectives of adopting a hydrogen economy. This necessitates a transition from a carbon-based energy system with significant dependence on coal to a clean and affordable energy. It was elucidated that most of the green hydrogen activities have taken place in industrialized countries with low-carbon footprint energy pathways.

Moreover, the hydrogen industry in South Africa must have a long-term framework for the acceptance of its technologies. To boost the energy sector while mitigating the carbon-based economy, the South African National Development Plan 2030 has been prioritized to invest in green energy production [26]. This is possible to create a sustainable market for a green hydrogen economy and accelerate decarbonization by modifying policies to accept green hydrogen. The transformation of the agricultural and industrial sectors, as well as value chain additions from the production, processing, and provision of green hydrogen energy, are expected to yield a return on both direct and indirect investments [27]. In addition, the availability of natural resources in the region will be significant to reduce the cost of production. Also, the country has a window of opportunity to develop platinum-based catalysts for hydrogen production to satisfy the demands of nations that have developed policies to integrate hydrogen into their economies. These economic benefits will have a crucial role in improving social welfare and infrastructure in the region. Furthermore, hydrogen and oxygen produced and captured can directly be used by the transportation and industrial sector as a primary source of energy.

## VI. Conclusion

In this study, a comprehensive review of contemporary trends in hydrogen production from non-carbonaceous technologies and renewable sources such as water and biomass were undertaken. The biomass thermochemical (gasification and pyrolysis) conversion technology was found not ecofriendly and energy-driven, which requires additional carbon-capture technology to mitigate its carbon footprint. Whereas biological (dark fermentation and photo-fermentation) conversion of biomass into hydrogen production has great potential to overcome the carbon footprint and energy barriers. It was elucidated that water electrolysis coupled with solar energy at a large scale is an economically viable technique for hydrogen production. This was considered the most economical and eco-friendly option to harness the renewable resources of South Africa for hydrogen production at a competitive price for economic growth. Thus, South Africa has optimal climatic conditions for solar power generation and wastewater resources to be employed for green hydrogen production.

Moreover, the prospect of a hydrogen-based economy will require all policy reforms to focus on establishing opportunities that improve current infrastructure, and skills, boost investor confidence and lower-carbon hydrogen. There is a need to transform existing gas/coal infrastructures and industrial seaports into hydrogen hubs. This is very prudent to invest in research and development for a sustainable green hydrogen production technology, given the hydrogen economy of South Africa is still at its earliest stage. Additionally, technoeconomic assessment is required to ascertain the advantages and disadvantages that are associated with a green hydrogen economy for socioeconomic growth and development. Combining hydrogen technologies with renewable energies and developing suitable catalysts to make hydrogen energy economically competitive is therefore necessary for more research to make technological advances.

**Authors' Contributions:** Conceptualisation EKT and SR; Methodology EKT and NGS; writing -original draft preparation NGS and EKT; writing -review and editing EKT and SR. All authors have read and agreed to the published version of the manuscript.

**Acknowledgements**: The authors thank the Green Engineering Research Group, under the Department of Chemical Engineering, and the Faculty of Engineering and the Built and Environment at Durban University of Technology, South Africa for technical support towards conducting this research.

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