



Research Article

A Bibliometric Study of the Evolution of Hydrogen Research: A Case of South Africa

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ABSTRACT

South Africa ranks among the top countries in global CO₂ emissions due to its dependence on coal. The global transition towards carbon-free energy has positioned hydrogen as a promising future fuel. This paper presents a bibliometric study of scholarly publications on hydrogen research (HR) in South Africa. Publications from 2001 to 2024 indexed in the Scopus database were extracted, refined, and analyzed using VOSviewer®. The study examined publication counts and trends, the most cited journals and publications, leading research sponsors, productive authors, institutions, countries, and key keywords. Additionally, the evolution, hotspots, and future directions of HR were identified and discussed. A total of 185 scholarly articles were sourced, with over 44% being journal articles. The most productive country, institution, journal, and author were South Africa (100 articles), Tshwane University of Technology (South Africa), the International Journal of Hydrogen (20 articles), and Linkov V. (8 articles), respectively. The most cited work, author, and journal were Ayodele (2019a), Bessarabov D., and the International Journal of Hydrogen, with 167, 437, and 828 citations, respectively. “Hydrogen” was the most frequently used keyword (26 occurrences). HR hotspots included electrolyzers, membranes, fuel cell development, and hydrogen production in South Africa, as well as their applications and impacts. Future HR efforts are expected to focus on green hydrogen production from renewable energy sources for export and hard-to-decarbonize sectors, social life cycle assessment, and practical applications of green hydrogen. Improved and sustained involvement of the South African government, research sponsors, policymakers and decision-makers, stakeholders, institutions, international investors, and researchers in HR is highly recommended to achieve carbon-free emissions and a significantly decarbonized economy.

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1. INTRODUCTION

Fossil fuels have served as primary energy sources for several centuries, beginning with coal and progressing to petroleum and natural gas. These fuels are concentrated in a few countries but consumed worldwide, resulting in a reliance on supplies from those nations. This dependency has led to rising fuel prices, supply instability, energy insecurity, and a small number of countries exerting control over global fuel prices. Additionally, the consumption of fossil fuels—particularly coal and petroleum derivatives in various combustion equipment and devices—is characterized by excessive carbon emissions and the release of other harmful gases and particulates, contributing to air pollution and poor air quality (Solomon O. Giwa, Nwaokocha, et al., 2023). This prolonged overdependence has negatively impacted the climate, environment, and human health, while also driving global temperature increases. Long before the recent global urgency to mitigate climate change and global warming, countries, organizations, and researchers sought alternatives to fossil fuels such as diesel, gasoline, and coal due to concerns over price volatility, supply limitations, environmental damage, and dependence (Saravanan et al., 2020; Tomar & Kumar, 2020). Prominent solutions proposed at that time include carbon-neutral biofuels (bioethanol, biodiesel, biogas, etc.) and zero-carbon solar energy (Amhamed et al., 2024; Solomon O. Giwa

et al., 2024; Solomon O Giwa & Taziwa, 2024; Tomar & Kumar, 2020).

The issue of renewable and sustainable energy and “decarbonization” (reducing emissions to low or zero carbon levels) did not become a global slogan or collective agenda until the business-as-usual consumption of fossil fuels—driven by population growth, economic development, technological advancement, and urban migration—revealed the trajectory of the Earth’s surface temperature rising beyond pre-industrial levels, which must be limited to below 2 °C and ideally maintained at a 1.5 °C increase (AlHumaidan et al., 2023; Wei et al., 2024). The Earth Summit (“Agenda 21”) held in Rio de Janeiro, Brazil, in 1992 marked the beginning of a coordinated global effort, with 178 countries committing to reduce emissions (Kakran et al., 2023). This was followed by significant milestones including the Kyoto Protocol (1997) in Kyoto, Japan; the Millennium Summit (2000) in New York, USA; and, more recently, the Conference of Parties (COP28). Supported by numerous organizations, agencies, nations, and councils, the 17 Sustainable Development Goals—established by the UN General Assembly in 2015—are now central to the global climate agenda (AlHumaidan et al., 2023; Hoffmann, 2019; Kakran et al., 2023). Consequently, there is a strong global push to adopt, implement, invest in, and finance renewable energy projects and initiatives aimed at addressing

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the challenges and impacts of climate change and global warming.

South Africa ranks seventh in the world and first in Africa in coal reserves, with over 15 billion tonnes (Jain & Jain, 2017). This has made coal the country's primary energy source, with over 85% of its electricity generated from coal-fired power plants (Pan & Dinter, 2017; Pollet et al., 2015). Coal is heavily relied upon for electric power production, the synthesis of liquid fuels and chemical products, and crude oil refining, contributing significantly to greenhouse gas emissions in South Africa's atmosphere (Pollet et al., 2015). As a result, the country has attracted global attention for emitting the highest amount of greenhouse gases in Africa and ranking twelfth worldwide (Bessarabov et al., 2012). According to the National Greenhouse Gas Inventory Report, the energy sector accounted for 79% of the 541 Mt CO₂e released in 2015, with power generation contributing 42% (Department of Environmental Affairs, 2018). In light of this, decarbonizing the energy sector—especially electricity generation—is crucial. This imperative has driven the integration of various renewable energy sources into South Africa's energy mix, particularly in power generation (Litheko et al., 2022).

South Africa is endowed with abundant renewable energy resources, particularly wind and solar energy, which can support electricity supply to the national grid and off-grid areas through renewable energy microgrids, as well as hydrogen production. As one of the best sunspots in the world, the country receives global horizontal irradiation of approximately 2300 kWh/m², direct normal irradiation around 3200 kWh/m², and over 2500 sunlight hours annually (Jain & Jain, 2017; Pan & Dinter, 2017). At an anemometer height of 10 meters, several regions in South Africa experience wind speeds ranging from 5 to 7 m/s (T. R. Ayodele, Mosetle, Yusuff, & Ogunjuvibe, 2021), with an estimated wind potential of 6,700 GW (Jain & Jain, 2017). In 2022, South Africa generated 6.2 TWh of solar energy, 9.7 TWh of wind energy, and 0.4 TWh from other renewables (Energy Institute, 2023), indicating the gradual integration of renewable energy into the national energy mix. The Integrated Resource Plan (IRP) 2019, which focuses on electricity infrastructure development, greenhouse gas emission reduction, and diversification of the energy mix, alongside the Renewable Energy Independent Power Producer Procurement Program (REIPPP) (Litheko et al., 2022), have both encouraged the adoption of renewable energy sources such as solar and wind for power generation. According to the IRP 2019, renewable energy is expected to account for about 40% of electricity generation by 2030, while the REIPPP aims to install 17.8 GW by the same year (Litheko et al., 2022).

Progress in research and the pursuit of viable renewable and sustainable fuels aligned with the low- and zero-carbon emissions agenda have positioned hydrogen as a promising future fuel. Hydrogen combusts without producing CO₂, CO, SO₂, PM₁₀, PM_{2.5}, black carbon, or other gaseous and particulate emissions, releasing only water as a byproduct. It has an energy content nearly four times that of gasoline and diesel, alongside other benefits (Solomon O Giwa & Taziwa, 2024). Various feedstocks—both renewable and non-renewable—and technological pathways have been reported for hydrogen production (AlHumaidan et al., 2023; Ikurowo et al., 2024). Gasification (using coal), steam methane reforming (using natural gas), and electrolysis (using water) are the primary technologies employed globally. The first two, based on non-renewable feedstocks, account for 96% of global hydrogen production, while electrolysis, relying on renewable

feedstocks, represents only 4%. These traditional methods are associated with approximately 830 Mt of CO₂ emissions annually (Younas et al., 2022). This indicates that much of the current production is grey hydrogen, characterized by high carbon footprints due to coal gasification and steam methane reforming. Global hydrogen production reached 115 Mt in 2018 and is projected to increase to 280 Mt by 2050 (AlHumaidan et al., 2023). The decarbonization of energy and other sectors worldwide is underway, supported by the expanded development and use of hydrogen for steel production, ammonia synthesis, transportation (including fuel cells, hybrid electric vehicles, forklifts, fuel cell trucks, and electric vehicles), methanol production, oil refining, and electricity generation (Ikurowo et al., 2024). Moreover, various countries and organizations are proposing and implementing projects aimed at achieving zero carbon emissions (Ikurowo et al., 2024; Kakran et al., 2023; Marouani et al., 2023; Roos, 2021).

Owing to the enormous potential of South Africa via renewable energy sources of solar and wind outside of coal and biomass to produce hydrogen (green, blue, and grey) to decarbonize the carbon-intensive economy, the country has long been involved, focused, and taking giant strides concerning hydrogen-related technologies as articulated in the National Hydrogen and Fuel Cells Technologies Research, Development and Innovation Strategy, Hydrogen South Africa agenda, and Hydrogen Roadmap program (Bessarabov et al., 2012; Bessarabov et al., 2017; Solomon O Giwa & Taziwa, 2024). In the context of South Africa, several scholarly studies have been conducted in relation to green hydrogen production prospects (Panchenko et al., 2023) to fuel hydrogen vehicles (T. R. Ayodele, Yusuff, et al., 2021), different hydrogen production technologies (T. R. Ayodele & Munda, 2019; Hoffmann, 2019; Moodley & Hoffmann, 2022), cost of stored and exported green hydrogen and ammonia from South Africa (Roos, 2021), integration of concentrated solar thermal technology to hydrogen production through electrolysis (Moodley & Hoffmann, 2022), effects of government structural and policy changes, hydrogen production projects, cost, transportation, and utilization (Kakran et al., 2023), analysis of power-to-gas technology applied to the road transport sector in terms of the compressed natural gas and hydrogen fuel cell vehicles (Litheko et al., 2022), cost-benefit and micro-grid electricity generation via coal gasification-proton exchange membrane fuel cell system (Gilani et al., 2021), hydrogen production via a coal gasifier incorporated to a high-temperature nuclear reactor (Botha et al., 2013), and optimized hybrid (grid-wind energy)-hydrogen energy system (Mukoni & Garner, 2022).

Bibliometric analysis is a branch of library and information sciences that employs statistical and quantitative methods to examine research articles retrieved from databases such as Scopus and Web of Science (Alagumalai et al., 2021). Because it uses a systematic approach to evaluate the evolution of various research fields based on related publications, bibliometric analysis is applicable across disciplines including science, engineering, information, and library sciences, among others. Moreover, it serves as a valuable tool for illuminating the origins, progression, and development of novel technologies and emerging fields of study (S.O. Giwa et al., 2022).

In this context, the aim of this study was to investigate the state of hydrogen research (HR) in South Africa through bibliometric analysis of the relevant academic literature. The

objective was to gain a comprehensive understanding of the characteristics of scholarly publications and associated features such as publication counts and trends; productivity and citation counts of contributing countries, authors, and institutions; citation metrics of involved journals and documents; and frequencies of author keywords. Additionally, the study provides insight into the evolution of HR in South Africa to identify topical and emerging research areas that can assist the scientific community and researchers in future endeavors. This study aligns with the Sustainable Development Goals, the just transition framework, and the African Union 2063 agenda (Mbanda et al., 2021), demonstrating South Africa's research activities and commitment toward energy decarbonization.

2. METHOD

2.1 Data mining

The study utilized data mined from Elsevier's Scopus® database, the world's largest research database (Omogbe et al., 2020). To extract relevant data, the search query—"natural hydrogen" OR "hydrogen resource*" OR electrolyser* OR electrolyzer* OR "fuel cell*" OR "hydrogen product*" OR "hydrogen generat*" OR "green hydrogen" OR "blue hydrogen" OR "grey hydrogen" AND "South Africa*"—was entered into the TITLE-ABS-KEY search field to capture hydrogen research (HR) related to South Africa. Data were collected for the period from 2001 to 2024. The raw results were further refined by source type and relevance, restricted to English-language publications, and limited to the year 2024. The mined data included research papers, reviews, conference proceedings, book chapters, and other document types. Data extraction was completed on May 20, 2024.

2.2 Data analysis

To perform network analysis using the refined mined data, VOS Viewer® was installed on a personal computer, and the data were imported into the software environment. Using VOS Viewer®, networks were generated at different intervals to analyze the productivity and citation counts of the involved

countries, authors, and institutions, as well as citations of relevant journals and documents, and the frequencies of author keywords (Omogbe et al., 2020). In the resulting networks, links connect the objects—such as authors, organizations, publications, countries, and keywords—as illustrated in the network map figures. The objects are represented by labeled bubbles, while the links are depicted by lines connecting these bubbles. Thicker lines indicate stronger connections between the linked objects, whereas larger bubbles and labels represent objects with higher weights. A flowchart summarizing this study is presented in Figure 1.

3. RESULTS AND DISCUSSION

3.1 Publication counts and trends

The publication counts and percentage of publications from 2001 to 2024 for hydrogen research (HR) in South Africa are shown in Figure 2. The mined data span 24 years, reflecting both the long journey and the forward-looking vision of HR in the country. In total, 185 scholarly articles were retrieved, comprising research articles (83), conference proceedings (63), notes (22), book chapters (8), conference review papers (5), and review papers (4). Scholarly outputs published in journals and conference proceedings accounted for 44.9% and 34.1%, respectively, indicating that approximately 75% of HR dissemination in South Africa occurs through these two channels. An average publication rate of 8 articles per year was recorded, highlighting the emerging global status of HR and its growing influence within the South African research community. Figure 2 shows an irregular pattern of rises and declines in publication numbers throughout the period, with no distinct trend. The slow start from 2001 to 2005 can be attributed to the limited acceptance and novelty of hydrogen as an energy carrier and its deployment in fuel cell vehicles. However, the last five years have seen a moderate increase in publications, accounting for over 42% of the total, with 2024 publications still being counted. The highest number of scholarly articles (21) was published in 2022, followed closely by 22 articles in 2023.

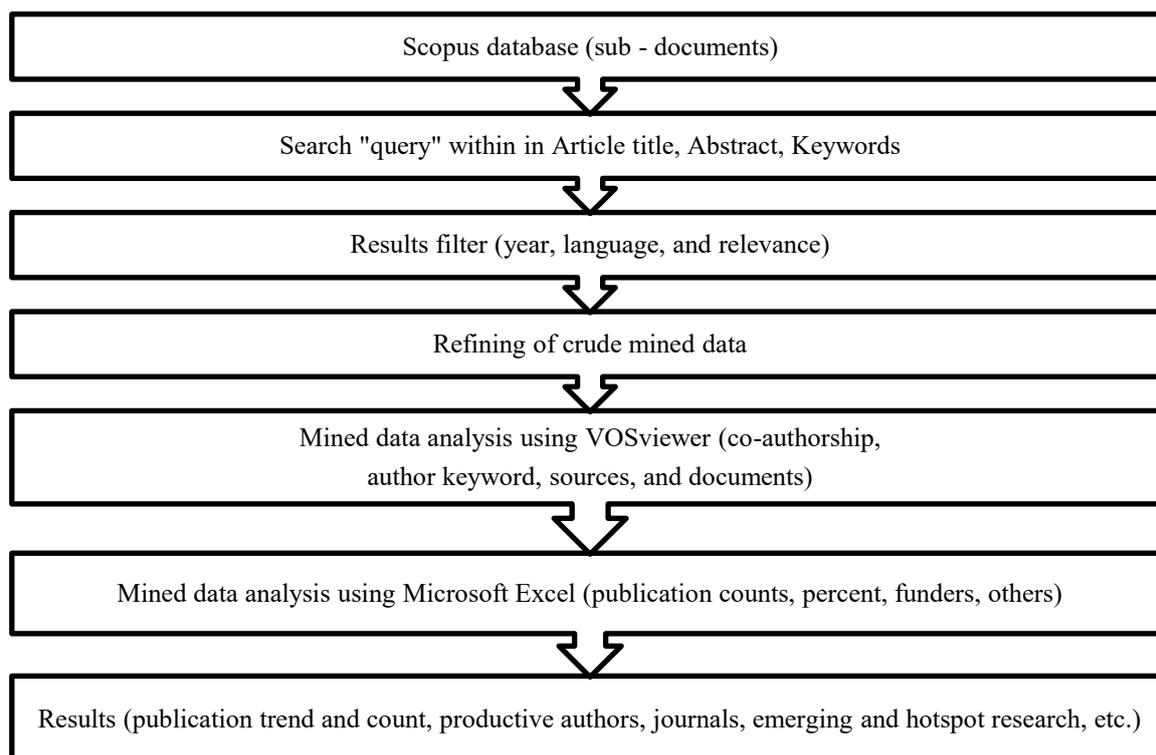


Figure 1. Flowchart of the present study.

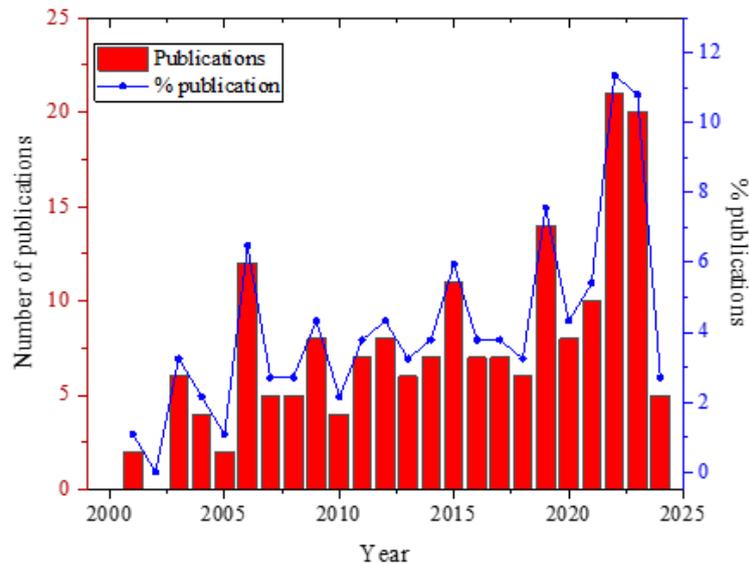


Figure 2. Number of scholarly publications and percent publications for hydrogen research.

Hydrogen research (HR) outputs in South Africa can be considered moderately satisfactory, given the relatively recent emergence of the field and the growing global emphasis on low- and zero-carbon emissions, which South Africa has embraced as a signatory to several climate- and emission-related treaties, agreements, and agendas. Scholarly publications are expected to increase significantly with the renewed global and national push for clean energy and electricity, where hydrogen plays a pivotal role. The South African government's active involvement in promoting energy decarbonization—through championing and implementing policy frameworks and strategies such as the Hydrogen South Africa program and the Hydrogen Roadmap—alongside financial support and investments, is anticipated to substantially boost hydrogen research, innovation, and development, thereby increasing HR publications.

3.2 Disciplines involvement

Table 1 presents the various disciplines contributing to hydrogen research (HR) in South Africa and the number of scholarly articles attributed to each. Of the 13 disciplines involved in HR, scholars in the Energy discipline were the most active, publishing 116 articles out of a total of 366 contributed by all disciplines. This accounts for 31.7% of the total publications. The high volume of publications underscores the central role of Energy, as it encompasses all forms of renewable energy sources—including hydrogen—and their deployment to reduce carbon footprints and related impacts across multiple dimensions. Moreover, hydrogen is attracting increasing attention as a renewable energy source, drawing scholars in Energy to focus on HR and hydrogen as a future fuel in this emerging research area.

The Energy discipline is followed by Engineering (17.8%, 65 articles), Environmental Science (8.5%, 31 articles), Business Management and Accounting (7.9%, 29 articles), Physics and Astronomy (6.8%, 25 articles), and Computer Science (5.5%, 20 articles). This distribution highlights the interdisciplinary nature of HR (as detailed in Table 1), reflecting the collaborative efforts needed to complement the research topic. Given the broad benefits and implications of energy, hydrogen studies are expected to involve experts from various disciplines. Accordingly, HR also engages fields beyond science and engineering, including Arts and Humanities, Medicine, Economics and Econometrics and

Finance, as well as Business Management and Accounting. These findings align with previous energy-related studies that identified the Energy discipline as the primary contributor to scholarly publications (Adedayo et al., 2021; Zhang et al., 2018).

Table 1. Disciplines involved in hydrogen research and the number of publications.

Disciplines	Number of publications
Energy	116
Engineering	65
Environmental Science	31
Business, Management and Accounting	29
Physics and Astronomy	25
Computer Science	20
Chemical Engineering	18
Social Sciences	13
Biochemistry, Genetics and Molecular Biology	9
Earth and Planetary Sciences	9
Chemistry	8
Mathematics	7
Materials Science	6
Agricultural and Biological Sciences	4
Economics, Econometrics and Finance	3
Arts and Humanities	1
Decision Sciences	1
Medicine	1

3.3 Citation counts of publications

Table 2 lists the top 10 most cited scholarly publications on hydrogen research (HR) in South Africa. Network analysis of the mined data revealed that, out of 185 published articles on HR, 69 had received at least 5 citations. The most cited work was Ayodele (2019b), titled "Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa," published in the *International Journal of Hydrogen Energy*, with 167 citations. This article alone accounted for 32% of the total citations among the top 10 cited papers, highlighting its significant impact and the pioneering exploration of green hydrogen production via wind-powered water electrolysis in South Africa. Following Ayodele (2019b), the works of Panchenko (2023), Touili (2020), Ayodele (2021b), Ayodele (2021c), and

Bessarabov (2017) received 94, 65, 61, 49, and 46 citations respectively. Six of the top 10 cited articles were published in the *International Journal of Hydrogen Energy*, indicating that research on South African HR is disseminated through a high-impact, reputable journal, reflecting the quality of the studies. Eight of these highly cited works focus on green hydrogen, while the remaining two address hydrogen infrastructure in South Africa. Additionally, nine of the top 10 cited papers are journal articles, with only one being a conference proceeding. The top 10 list includes six research papers and four review articles, with Ayodele and collaborators contributing to five of them. Furthermore, South African scholars are the sole authors of eight of these top 10 cited papers, while the remaining two are authored by researchers from Russia and Morocco. This distribution underscores the strong involvement and contribution of South African researchers in advancing hydrogen research aimed at achieving low and zero carbon emissions within the country.

3.4 Citation counts of journals

Table 3 presents the 10 most cited publication outlets for hydrogen research (HR) in South Africa. Network analysis of the mined data identified 118 journals involved in HR, with 76 journals having at least one cited article. The *International Journal of Hydrogen Energy* stands out as the most cited journal, with 828 citations from 20 articles. As shown in Table 3, this journal remains the leading platform for disseminating

HR findings. Its high average citation rate of 41.4 per article reflects the quality and impact of the scholarly work published there, attracting significant attention across diverse audiences. This aligns with earlier observations that six of the top-cited HR articles in South Africa were published in this journal.

Other prominent journals in the top 10 list include *Journal of Energy in Southern Africa*, *Journal of Renewable and Sustainable Energy*, *Applied Energy*, *Applied Thermal Energy*, *Energies*, and *International Journal of Sustainable Engineering*, with citation counts of 27, 23, 15, 15, 6, and 6 respectively. Among these top outlets, seven are journals, while the remaining three are conference proceedings or books. The leading journals primarily focus on energy systems and technologies, energy modeling and simulation, energy economics and policies, environmental pollution and emissions, and energy development—areas closely related to renewable energy deployment.

Notably, the *Journal of Energy in Southern Africa*, based in South Africa, ranks second among HR journals with 27 citations from 4 articles. This highlights the quality of domestic energy research, including HR, published in the local journal. Its impact factor of 1.3 and Q3 ranking further affirm its status as a reputable, high-impact outlet for HR dissemination. Additionally, five of the seven leading HR journals are ranked Q1, with impact factors above 3 and CiteScores exceeding 5, underscoring that South African HR research is being published in highly regarded and globally recognized journals.

Table 2. Most cited articles in hydrogen research.

Publications	Title	Citations
Ayodele (2019a) (T. R. Ayodele & Munda, 2019)	Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa.	167
Panchenko (2023) (Panchenko et al., 2023)	Prospects for the production of green hydrogen: review of countries with high potential.	94
Touili (2020) (Touili et al., 2020)	Analysis of the yield and production cost of large-scale electrolytic hydrogen from different solar technologies and under several Moroccan climate zones.	65
Ayodele (2021a) (T. R. Ayodele, Mosetlhe, Yusuff, & Ntombela, 2021)	Optimal design of wind-powered hydrogen refuelling station for some selected cities of South Africa.	61
Ayodele (2021c) (T. R. Ayodele, Mosetlhe, Yusuff, & Ogunjuyigbe, 2021)	Off-grid hybrid renewable energy system with hydrogen storage for South African rural community health clinic.	49
Bessarabov (2017) (Bessarabov et al., 2017)	South African hydrogen infrastructure (HySA infrastructure) for fuel cells and energy storage: overview of a project portfolio.	46
Ayodele (2019b) (T. R. Ayodele & Munda, 2019)	The potential role of green hydrogen production in the South Africa energy mix.	23
Ayodele (2021b) (T. R. Ayodele, Yusuff, et al., 2021)	Hydrogen production using solar energy resources for the South African transport sector.	6
Mukoni (2022) (Mukoni & Garner, 2022)	multi-objective non-dominated sorting genetic algorithm optimization for optimal hybrid (wind and grid)-hydrogen energy system modelling	6
Bessarabov (2012a) (Bessarabov et al., 2012)	hydrogen infrastructure within HySA national program in South Africa: road map and specific needs	4

Table 3. Most cited journals in hydrogen research.

Journals	Documents	Citations	Average citations	IF	Q	CS
International Journal of Hydrogen Energy	20	828	41.4	7.2	1	13.5
Journal of Energy in Southern Africa	4	27	6.75	1.3	3	-
Journal of Renewable and Sustainable Energy	1	23	23	2.5	2	5.3
Applied Energy	2	15	7.5	11.2	1	21.2
Applied Thermal Engineering	1	15	15	6.4	1	11.3
Energies	1	6	6	3.2	1	6.2
International Journal of Sustainable Engineering	1	6	6	3.7	1	5.5
Gasification: Chemistry, Processes and Applications	1	4	4			
WHEC 2012 Conference Proceedings - 19th World Hydrogen Energy Conference	2	4	2			
Hydrogen in an International Context: Vulnerabilities of Hydrogen Energy in Emerging Markets	1	2	2			

3.5 Authors involvement

The number of scholarly publications and citation counts of authors reflect their expertise in a particular field as well as the visibility and impact of their research productivity. Table 4 presents the results of the co-authorship analysis based on the mined data, showing the involvement of authors in hydrogen research (HR) in South Africa. A total of 469 authors contributed to HR publications, with 365 authors having at least one citation.

The five most productive authors are Linkov V., Pasupathi S., Bessarabov D., Pollet B.G., and Lototsky M., with 8, 8, 7, 6, and 4 articles respectively. Linkov V. and Pasupathi S. are co-leading authors, each publishing 8 articles, although Linkov V. has a slightly higher citation count (95 versus 88). Both are affiliated with the South African Institute for Advanced Materials Chemistry at the University of the Western Cape. Their research focuses on electrocatalysis, electrolysis, fuel cells, electrolyzers, battery development and applications, hydrogen storage, and CO₂ capture and utilization.

Eight of the top 10 leading authors are based in South Africa, collaborating extensively, particularly Linkov V., Pasupathi S., Bessarabov D., and Lototsky M. Their h-index values—41, 32, 39, 52, and 40 respectively—reflect the number of publications cited and indicate the high quality and impact of their work within the research community. Among them, Bessarabov D. is the most cited author with 437 citations, followed by Linkov V. (95 citations) and Pasupathi S. (88 citations) in the context of South African HR.

Figure 3 illustrates the co-authorship network map, highlighting the most productive authors and the extent of collaboration. The authors are grouped into six clusters, represented by different bubble colors. Linkov V., depicted by the largest sky blue bubble, is the most published author. Other key contributors such as Pasupathi S. (sky blue), Bessarabov D. (purple), Pollet B.G. (sky blue), Mathe M. (yellow), and Mathe M.K. (orange) are also shown.

The strong research collaboration and shared interests among Linkov V., Pasupathi S., and Pollet B.G. are evident from their placement in the same cluster (sky blue), the thickness of connecting lines, and proximity on the map. Linkov V. also collaborates with Williams M. and Nechaev A. (teal green cluster), and Lototsky M.K. (red cluster), among others. Similarly, Bessarabov D. is linked to Mathe M., Van Niekerk F., and Modisha P.M. (yellow and purple clusters), as well as Pollet B.G. The total link strength values in Table 4 quantify the extent of each author's collaborative research activity, with Linkov V., Pasupathi S., and Bessarabov D. leading with total link strengths of 48, 44, and 38 respectively.

3.6 Institutional involvement

The involvement of various institutions in hydrogen research (HR) in South Africa, as measured by scholarly publications and research collaboration, was analyzed using the co-authorship of institution scheme in VOS Viewer®. Table 5 summarizes the leading institutions, the number of articles published, citations attracted, and average citations.

The network analysis identified 282 institutions participating in HR studies related to South Africa, but only nine institutions had a minimum of two articles with at least two citations each. This limited collaboration is evident in the low number of co-authored publications between institutions,

as all institutions listed in Table 5 have only two articles each, and Figure 4 shows no connecting links between them.

Seven of the top nine productive institutions are based in South Africa, with Tshwane University of Technology leading in citations (190 citations). Additionally, South African institutions occupy the top three positions for citation counts related to HR. However, the co-authorship network map in Figure 4 clearly highlights the lack of inter-institutional collaboration, as there are no visible links connecting these institutions.

This absence of strong collaborative ties underscores an urgent need to foster more sustainable and extensive research partnerships among South African institutions and beyond. Expanding collaboration both within the country and internationally will facilitate knowledge sharing, improve the quality and impact of research, and encourage joint initiatives and funding opportunities to advance hydrogen research aligned with the low and zero carbon emissions agenda.

3.7 Countries involvement

The scholarly involvement of different countries in hydrogen research (HR) related to South Africa, including their publication output and collaboration, was analyzed using the co-authorship of country scheme.

Table 6 presents the number of articles, citation counts, and average citations for the 14 most productive countries based on the mined data. Among the 42 countries involved in HR, 38 had at least one article with one citation. The five most productive countries are South Africa, the United States, Germany, Nigeria, and the United Kingdom, with 100 (1,783 citations), 14 (98 citations), 8 (436 citations), 8 (150 citations), and 8 (116 citations) articles respectively. South Africa leads both in productivity and citation counts, reflecting its significant contribution to the body of knowledge and focused research addressing its unique hydrogen-related challenges.

The country's outputs align with global best practices and high standards, resulting in impactful scholarly work that has garnered considerable international recognition. From Table 6, it is evident that while hydrogen is emerging as a key future fuel, countries from all continents have participated in HR connected to South Africa, albeit with relatively low collaborative outputs. Nonetheless, there is strong potential for increased research collaboration with these and other countries, which would enhance cooperative efforts and funding opportunities aimed at developing a circular and hydrogen economy to effectively address climate change challenges.

Figure 5 presents a network map of the co-authorship by country, highlighting the most productive countries and the extent of their research collaboration and outputs related to hydrogen research in South Africa.

The network analysis groups these countries into seven clusters. South Africa, shown as the largest bubble in sky blue, stands as the central focus of this study. Other prominent bubbles represent the United States (green), Germany (red), Nigeria (sky blue), and France (yellow), identifying them as the top productive countries. The total link strengths listed in Table 6 show South Africa with a value of 30, followed by the USA and Nigeria both at 10, Germany at 8, and France at 6. These numbers reflect the strength of collaborative research connections with South Africa, contributing to joint scholarly outputs.

Table 4. Co-authorship of authors involved in hydrogen research.

Authors	Cluster	Total link strength	Documents	Citations	Average citations
Linkov, V.	3	48	8	95	11.9
Pasupathi, S.	3	44	8	88	11.0
Bessarabov, D.	5	38	7	437	62.4
Pollet, B.G.	3	19	6	48	8.0
Lototskyy, M.	3	21	4	38	9.5
Bujlo, P.	3	22	3	46	15.3
Human, G.	2	23	3	51	17.0
Mathe, M.	4	20	3	16	5.3
Mathe, M.K.	7	7	3	2	0.7
North, B.	4	20	3	16	5.3

Table 5. Co-authorship of institutions involved in hydrogen research.

Institutions	Cluster	Documents	Citations	Average citations
Tshwane University of Technology, South Africa.	3	2	190	95
University of South Africa, South Africa.	1	2	110	55
University of Cape Town, South Africa.	2	2	90	45
Sotacarbo s.p.a., grande miniera di serbariu, Italy.	7	2	70	35
University of Ibadan, Nigeria.	1	2	67	33.5
Council for Scientific and Industrial Research, South Africa.	6	2	48	24
North-West University, South Africa.	5	2	14	7
Mangosuthu University of Technology, South Africa.	4	2	12	6
University of the Western Cape, South Africa.	8	2	0	0

Table 6. Co-authorship of countries involved in hydrogen research.

Countries	Cluster	Total link strength	Documents	Citations	Average citations
South Africa	3	30	100	1783	17.8
United States	2	10	14	98	7.0
Germany	1	7	8	436	54.5
Nigeria	3	10	8	150	18.8
United Kingdom	2	8	8	116	14.5
France	4	6	6	118	19.7
Australia	4	1	3	270	90.0
China	2	3	3	25	8.3
India	7	3	3	30	10.0
Malaysia	1	4	3	39	13.0
Poland	5	4	3	17	5.7
Egypt	6	2	2	136	68.0
Indonesia	1	6	2	55	27.5
Japan	6	1	2	8	4.0

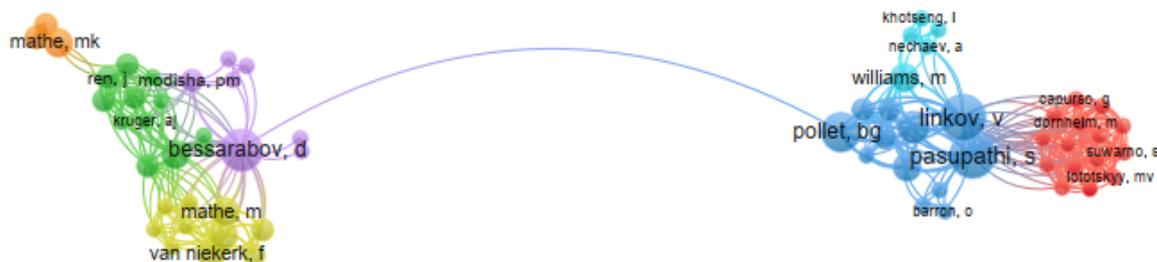


Figure 3. Network analysis of co-authorship of authors for hydrogen research.

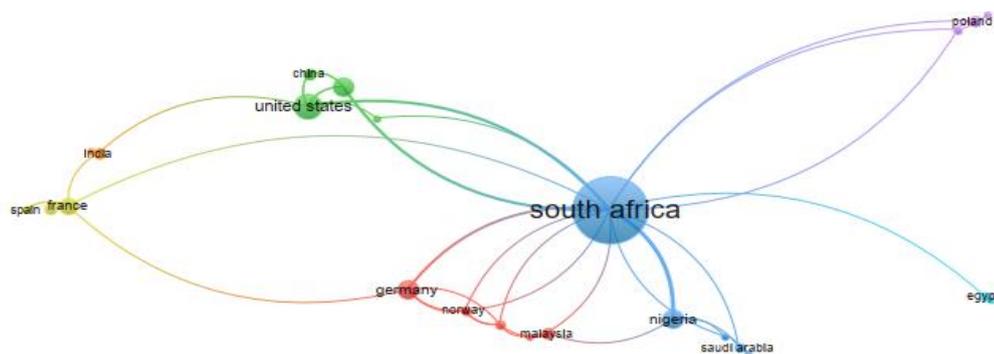


Figure 4. Network analysis of co-authorship of countries for hydrogen research.

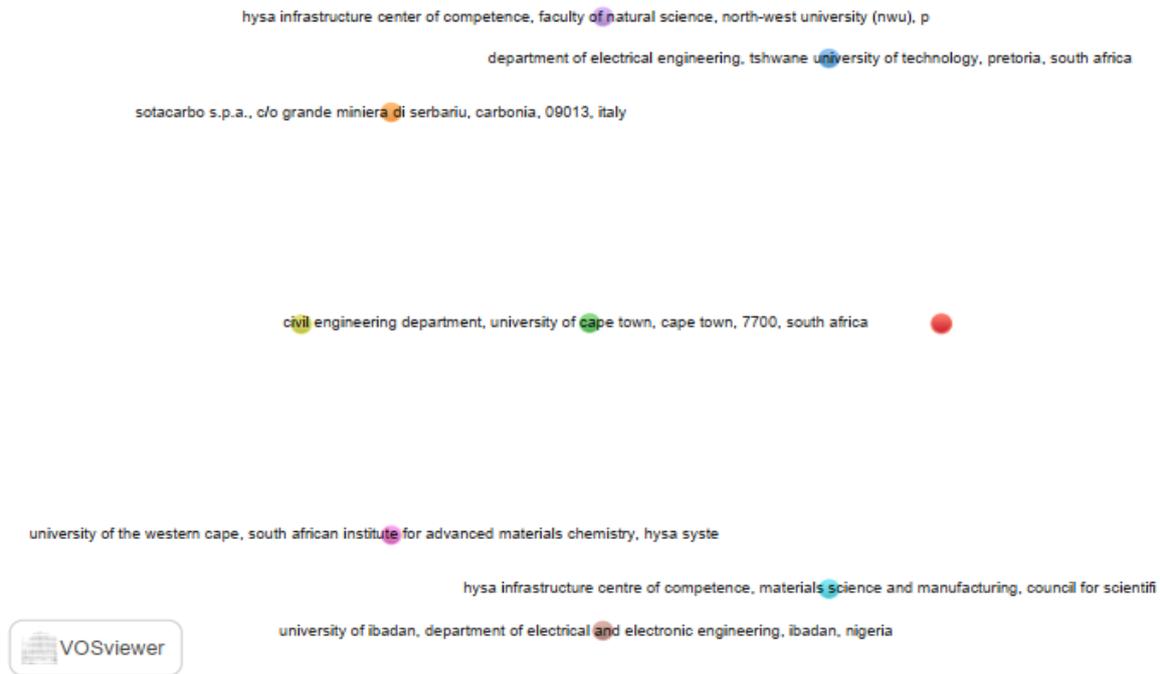


Figure 5. Network analysis of co-authorship of institutions for hydrogen research.

However, the map also reveals relatively weak collaboration indicated by the noticeable distances between South Africa and countries like the USA, Nigeria, Germany, China, Norway, Malaysia, and Saudi Arabia. Even weaker connections exist between South Africa and France, India, Egypt, Poland, and Spain, which are situated further apart on the map. These observations underscore the need to strengthen research partnerships between South African scholars and their international counterparts, which would enrich hydrogen research collaborations and boost shared scientific productivity.

3.8 Author keywords

Keywords in scholarly articles serve as root terms that express the central themes and research directions of the publications. Network analysis of keywords is a powerful tool for identifying research hotspots and emerging trends (Zhang et al., 2018). In this study, a network analysis based on the co-occurrence of author keywords in hydrogen research (HR) related to South Africa was conducted, with the 15 most frequently used keywords listed in Table 7. Across all publications, 426 unique keywords were used, with 71 appearing more than twice.

The six most common keywords are Hydrogen (26 occurrences), Fuel Cells (17), South Africa (13), Renewable Energy (12), Energy (8), and Green Hydrogen (8). Hydrogen, being the most frequently used keyword, clearly reflects the core focus of this study. Taken together, the top keywords suggest that hydrogen is viewed as a promising renewable energy solution to South Africa's energy challenges. Research predominantly focuses on hydrogen production from solar energy, wind energy, biogas, wastewater, and biomass, often described as green hydrogen, with applications in fuel cells. Key production technologies such as electrolysis and gasification are heavily studied alongside themes like efficiency (with combined heat and power as a key method), sustainability, optimization, economic analysis, and greenhouse gas emissions. The research hotspots revolve around developments in electrolyzers, membranes, and fuel cells; green hydrogen production using solar and wind energy;

and the techno-economic, environmental, and carbon footprint impacts of these technologies within South Africa.

Figure 6 presents the network map of author keyword co-occurrence, illustrating the relationships among the most used keywords in South African HR literature. The largest bubble (purple) corresponds to Hydrogen, underscoring its dominance. Other significant bubbles include Fuel Cells (brown), South Africa (red), Renewable Energy (sky blue), Green Hydrogen (sky blue), and Energy (purple). The strength of connections is reflected in the total link strengths: Hydrogen (75), Fuel Cells (44), South Africa (38), Energy (26), Renewable Energy (21), and Green Hydrogen (12). These link strengths indicate how often these keywords co-occur with others across different authors' abstracts, demonstrating their centrality in the research landscape.

3.9 Sponsors involvement

Funding from agencies, organizations, and universities plays a vital role in driving national, economic, technological, and developmental progress—especially in hydrogen research (HR) in South Africa. Adequate financial support is essential to promote and implement hydrogen as a promising fuel that can power the global transition toward low- and zero-carbon economies.

Table 8 lists the top sponsors of HR in South Africa. Among the top 10 sponsors, a total of 43 scholarly articles were published, with the National Research Foundation (South Africa) leading by supporting 9 articles. Notably, five of the top sponsors and seven out of the top 10 are South African-based institutions. This reflects a relatively low level of international involvement and overall commitment to HR—an important factor in tackling climate change, ensuring energy access, and advancing sustainable development in line with the United Nations' Sustainable Development Goal 7 (Aziz et al., 2023). It also highlights the challenges South Africa faces in meeting its ambitious low-carbon target for 2030 and zero-carbon goal by 2050 (Mbanda et al., 2021). These findings emphasize the urgent need for increased funding and stronger support for HR within the country.

Table 7. Most keywords used hydrogen research.

Keywords	Cluster	Total link strength	Occurrences	Average citations
Hydrogen	9	75	26	20.0
renewable energy	4	21	12	26.4
South Africa	8	38	13	28.0
Fuel cells	15	44	17	13.7
Energy	7	26	8	14.1
Green hydrogen	4	12	8	18.4
Solar energy	1	14	6	49.5
Wind energy	1	18	5	65.8
Biogas	5	14	4	6.3
Biomass	5	14	4	5.8
Optimization	8	10	4	44.3
Sustainability	4	9	4	6.3
Wastewater	5	6	4	26.8
Combined heat and power	5	6	3	1.0
Distributed generation	5	3	3	10.7
Economic analysis	2	6	3	78.0
Efficiency	8	9	3	5.0
Electrolysis	7	11	3	30.0
Gasification	3	7	3	30.7
Greenhouse gas Emissions	6	5	3	52.7

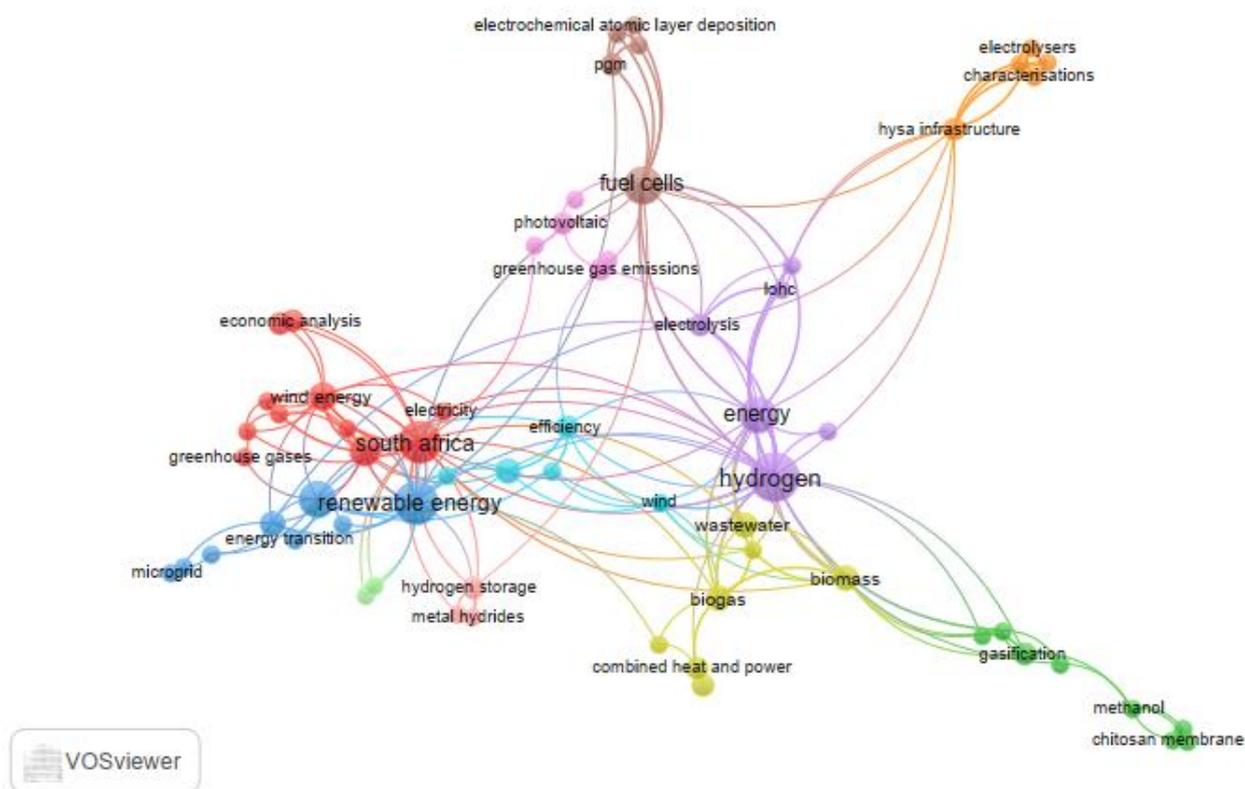


Figure 6. Network analysis of co-occurrence author keywords for hydrogen research.

Table 8. Hydrogen research funders.

Funding institutions and Agencies	Number of publications
National Research Foundation, South Africa	9
Council for Scientific and Industrial Research, South Africa	7
Department of Science and Innovation, South Africa	4
University of Cape Town	4
Water Research Commission	4
Department of Science and Technology, Government of Kerala	3
Department of Science and Technology, Ministry of Science and Technology, India	3
Department of Science and Technology, Republic of South Africa	3
Horizon 2020	3
University of the Western Cape	3

3.10 Hydrogen research evolution

Figure 7 illustrates the evolution of hydrogen energy (HE) research in South Africa over more than 23 years, based on the co-occurrence of author keywords. The research development is grouped into four clusters, each represented by a different bubble color: navy blue, green, lemon, and yellow, corresponding to the periods 2001–2014, 2014–2018, 2018–2021, and 2021–2024, respectively.

The navy-blue cluster (2001–2014) includes keywords such as gasification, pyrolysis, methanol, palladium group metals (PGMs), electrochemical layer deposition, chitosan membrane, water content, distributed generation, membrane resistance, electrocatalysis, electrolyzers, proton-electron membrane electrolysis, characterizations, and diagnostic tools. These terms reflect the research focus during this period on hydrogen production through gasification and pyrolysis techniques (using coal and methanol as feedstocks), as well as the development, operation, and characterization of electrolyzer components.

In particular, chitosan membranes and proton-electron membrane electrolysis were key areas of study. The large deposits of PGMs in South Africa, along with efforts to add value through beneficiation, have driven the development of membranes used in electrolyzers and fuel cell components. This work partly led to the creation of the National Hydrogen and Fuel Cells Technologies Research, Development, and Innovation Strategy, known as “Hydrogen South Africa” (HySA) (Bessarabov et al., 2017; Human et al., 2011). HySA is a flagship national program comprising three centers—HySA Systems, HySA Catalyst, and HySA Infrastructure—aimed at building South African expertise, intellectual property, and products to secure the country’s role in the rapidly growing global hydrogen and fuel cell technology sector (Bessarabov et al., 2012).

The green bubble cluster represents the author keywords most prominent in scholarly articles published during 2017–2019. Keywords in this cluster include syngas, hydrogen

production, biomass, fuel cells, water electrolysis, biohydrogen, dark fermentation, energy management, optimization, rural electrification, greenhouse gas emissions, platinum, coal, electric vehicles, South Africa, and HySA infrastructure. These keywords indicate a research focus on hydrogen production from biomass through syngas generation, biohydrogen, and dark fermentation technologies. Energy management and optimization related to hydrogen production and the use of hydrogen-powered proton exchange membrane (PEM) fuel cells for rural electrification were key topics during this period. Additionally, the application of fuel cell technology to electric vehicles gained considerable attention between 2017 and 2019. Studies on water electrolysis and coal gasification as hydrogen production methods aimed at reducing greenhouse gas emissions were also intensified. The beneficiation of platinum to produce electrolyzers and fuel cells, aligned with the HySA infrastructure, was another important research area during this time (Pan & Dinter, 2017).

The lemon bubbles represent key keywords from hydrogen-related studies conducted between 2019 and 2021. These include hydrogen, renewable energy, South Africa, energy, solar energy, wind energy, electricity, efficiency, electrolysis, biogas, wastewater, LOHC (liquid organic hydrogen carrier), economic analysis, photovoltaic, transport sector, and hydrogen refueling station. During this period, there was a growing focus on hydrogen as a renewable energy source in South Africa, particularly through electrolysis powered by wind and solar (photovoltaic) energy (Hoffmann, 2019). Research also concentrated on the efficiency and economic feasibility of hydrogen-based electricity generation systems. Additionally, biogas and wastewater were explored as alternative feedstocks for hydrogen production within the country. The studies addressed hydrogen storage solutions using liquid organic hydrogen carriers (LOHC) and examined its role in decarbonizing the transport sector, including the development of hydrogen refueling stations (T. R. Ayodele, Mosetlhe, Yusuff, & Ntombela, 2021; T. R. Ayodele & Munda, 2019a; T. R. Ayodele & Munda, 2019b).

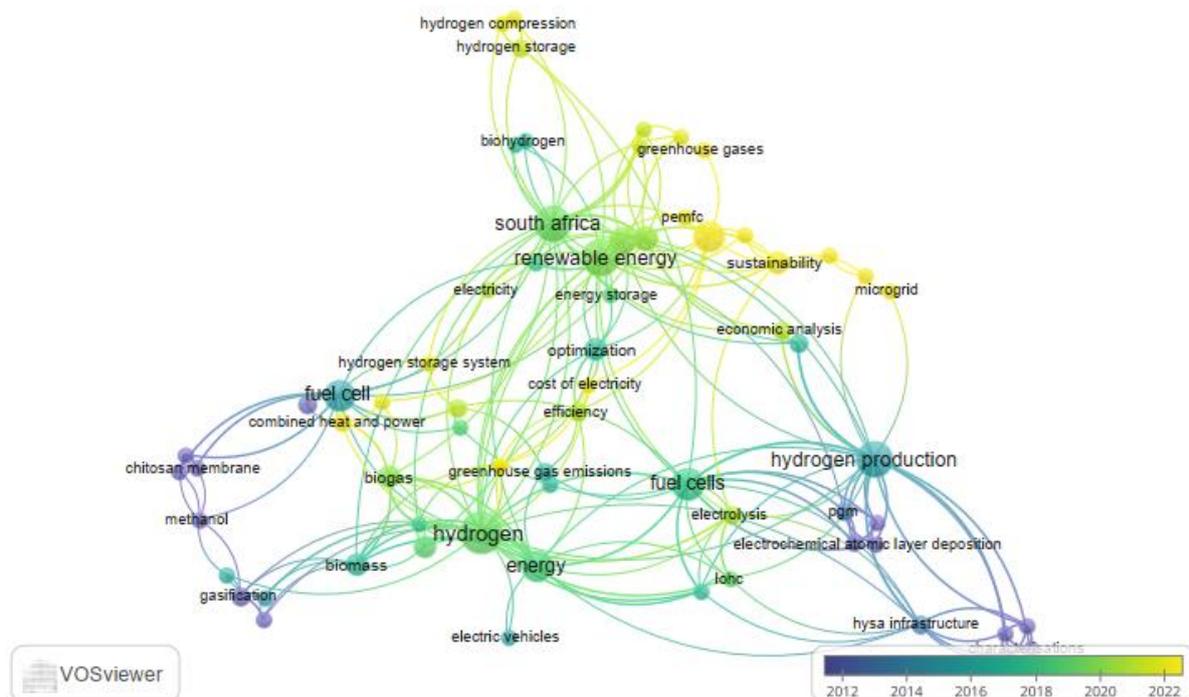


Figure 7. Temporal evolution of author keywords for hydrogen research.

The yellow bubble cluster represents the main keywords from hydrogen research conducted between 2021 and 2024. These include green hydrogen, sustainability, cost of electricity, combined heat and power, energy efficiency, wind, hydrogen storage systems, hydrogen compression, metal hydrides, greenhouse gases, hydrogen vehicles, microgrids, PEMFC (proton-exchange membrane fuel cell), energy transition, and social life cycle assessment. During this period, there has been a strong focus on green hydrogen — regarded as the cleanest form of hydrogen — produced from South Africa’s abundant solar and wind resources. Its potential for driving the energy transition toward zero-carbon fuels is especially significant for hard-to-decarbonize sectors such as transport and manufacturing (steel and cement) (T. R. Ayodele, Yusuff, et al., 2021; Litheko et al., 2022; Moodley & Hoffmann, 2022; Panchenko et al., 2023; Trollip et al., 2022). Research has also emphasized energy sustainability, the cost of hydrogen-derived electricity, and social life cycle assessments related to hydrogen-based electricity production. Additionally, combined heat and power technologies have been explored as methods to improve overall energy system efficiency (Hanto et al., 2021; Marouani et al., 2023; Moodley & Hoffmann, 2022; Roos, 2021). Studies on hydrogen storage technologies, particularly hydrogen compression and metal hydrides, have continued to advance alongside efforts to deploy PEMFCs in hydrogen-powered vehicles (Marouani et al., 2023; Panchenko et al., 2023; Roos, 2021). Central to hydrogen research (HR) in South Africa is the production of hydrogen through electrolysis of water using solar and wind energy, as well as gasification processes utilizing coal and biomass. Research also focuses on the development of membranes, electrolyzers, fuel cells, and their components, leveraging South Africa’s abundant platinum group metal (PGM) reserves. Additionally, hydrogen storage technologies and the deployment of proton-exchange membrane fuel cells (PEMFC) in transport (electric and hydrogen vehicles) and power sectors (including rural electrification) are key areas of study. Efforts extend to improving the efficiency of hydrogen-based electricity generation systems, alongside economic analyses and assessments of carbon emissions. The rise of green hydrogen is driven by the country’s rich renewable energy resources—wind, solar, and biomass—supporting domestic energy decarbonization, export potential, and economic growth. Emerging and future research trends include the integration of green hydrogen in microgrids to provide clean electricity for remote and decentralized communities, social and environmental life cycle assessments of hydrogen-powered electricity systems, utilization of biomass (organic waste and wastewater) for hydrogen production, and practical green hydrogen application projects. Notably, these priorities align closely with the objectives outlined in the HySA Roadmap (Department of Science & Innovation, 2021). It is worth noting that the literature search used in this present study was limited to the Scopus database as there were other databases such as Web of Science, Google Scholar, etc. Also, publications in English language were used in this work with very few articles published in other languages. In addition, the VOS viewer was used as a network analysis tool against other software such as Biblioshiny and Cite Space.

4. Conclusions

A bibliometric analysis of hydrogen research (HR) in South Africa was conducted based on 185 scholarly articles published across 118 journals, involving 42 countries, 468 authors, and

282 institutions. Journals accounted for over 44% (83 articles) of the total publications, with the highest annual output of 21 articles recorded in 2023. The average publication rate stands at 7.7 articles per year, reflecting a gradual but steady growth in HR within the country. Regarding scholarly contributions, the leading discipline is Energy, while South Africa leads as the most productive country with 100 articles. The Tshwane University of Technology is the top institution, the International Journal of Hydrogen ranks as the most prolific journal with 20 articles, and Linkov V. is the most productive author with 8 publications.

The most cited work is by Ayodele (2019a), with 167 citations, while Bessarabov D. holds the highest citation count among authors (437 citations). The International Journal of Hydrogen is also the most cited journal, attracting 828 citations. “Hydrogen” is the most frequently used author keyword, appearing 26 times. Research hotspots focus on electrolyzer, membrane, and fuel cell development, as well as green hydrogen production via electrolysis and gasification using solar and wind energy in South Africa. Applications and studies emphasize techno-economic analysis, environmental impact, and carbon footprint assessment. Future research priorities include green hydrogen production from renewable resources for export, clean electricity generation, deployment in the transport sector, social life cycle assessment, environmental life cycle assessment of hydrogen-powered systems, and practical green hydrogen projects. To advance these goals, stronger and sustained engagement is needed from the South African government, research sponsors, policymakers, stakeholders, institutions, international investors, and researchers. Their collaborative efforts are vital for achieving zero carbon emissions and advancing South Africa toward a significantly decarbonized economy.

5. Acknowledgments

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Nomenclature

AU – Africa Union
 COP28 – Conference of Parties 28
 HR – Hydrogen Research
 HySA – Hydrogen South Africa
 IRP – Integrated Resource Plan
 LOHC – Liquid Organic Hydrogen Carrier
 PEM – Proton Electron Membrane
 PEMFC – Proton Electron Membrane Cell
 PGMs – Platinum Group Metals
 REIPPP – Renewable Energy Independent Power Producer Procurement
 UN – United Nations

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