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Review article

Trends and determinates of hydrogen energy acceptance, or adoption research: A review of two decades of research

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ABSTRACT

A promising technological solution to the pressing problem of decarbonizing the global energy system is clean hydrogen. Therefore, understanding how the public feel about hydrogen is essential to its success, just like with any new technology. This paper offers the findings of a bibliometric and systematic review that examined the literature on the variables affecting the acceptance of hydrogen energy. A total of 108 documents published from 2003 to 2023 were used for the bibliometric analysis using the Biblioshiny software in the R package. The study shows a steady growth in hydrogen energy acceptance research, with 350 authors and a 12.96% international co-authorship rate. The literature on hydrogen acceptance reveals that limited public awareness, perceived usefulness, safety, cost, and health benefits influence one's acceptance. Acceptance of hydrogen was also found to be highly dependent on financial policies, industry support for climate protection, government confidence, and efficient communication and engagement. Japan, Germany, and China dominate hydrogen energy research globally, while some European countries also contribute significantly. However, regional acceptance gaps exist in Africa and South America.

Introduction

Concerns regarding the energy sector's economic, environmental, and social performance (such as energy security and climate change) highlight the necessity of moving toward a sustainable energy system [1–3]. Hydrogen is rapidly advancing as a critical component in the ongoing global energy transition [4]. Hydrogen production technologies can be broadly divided into conventional (fossil-fuel-based) and emerging (renewable-based or low-carbon) methods. The most widely used methods for hydrogen production are steam methane reforming (SMR) and coal gasification [5]. SMR involves the reaction of natural gas (methane) with high-temperature steam to produce hydrogen, carbon monoxide, and a small amount of carbon dioxide [6]. Coal gasification is another conventional process that converts coal into synthesis gas (syngas), which is then refined to extract hydrogen [7]. Electrolytic hydrogen production technologies, such as alkaline electrolysis [8], polymer electrolyte membrane (PEM) electrolysis [9], and solid oxide electrolysis [10], use electricity to split water into hydrogen and oxygen. Emerging methods include photoelectrochemical water splitting, which uses light-absorbing semiconductors [11], thermochemical water splitting driven by high-temperature heat [12], and biological hydrogen production by microorganisms [13].

Hydrogen technology holds significant promise as an alternative energy source, but it also faces several key challenges that must be addressed. One of the primary weaknesses of hydrogen is the high cost associated with its production, storage, and distribution [14]. The most common method of producing hydrogen is SMR, which involves extracting hydrogen from natural gas. This energy-intensive process can

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result in significant greenhouse gas emissions [15]. Alternative methods, such as water electrolysis powered by renewable energy, are cleaner but more expensive [16]. Storing and transporting hydrogen also pose difficulties, as it requires either high-pressure tanks or cryogenic liquefaction, which add to the overall cost [17]. In addition, the lack of a widespread hydrogen fueling infrastructure is another significant hurdle, with only a few hydrogen stations available in most regions, limiting the practicality of hydrogen-powered vehicles [18].

However, hydrogen technology also has several notable advantages that make it an appealing option for the future of energy. Perhaps most importantly, hydrogen produces only water as a byproduct when used in fuel cells, making it an exceptionally clean and environmentally friendly energy source [19]. Hydrogen also has a high energy density, meaning that a relatively small amount can store a significant amount of energy, making it an efficient fuel for transportation and other applications [14]. Additionally, hydrogen can be produced from various sources, including water, natural gas, and waste products, providing flexibility and reducing dependence on finite fossil fuels [20]. Proponents of hydrogen technology also argue that as production methods improve and infrastructure is built out, the costs associated with hydrogen will decrease, making it a more viable and competitive option compared to traditional fossil fuels and other alternative energy sources.

International policymakers recognize hydrogen as a crucial energy source for achieving climate change pledges and net-zero targets. Hydrogen energy technologies (HETs) are essential for industrial and transportation applications, supporting international efforts to reduce carbon emissions and national energy transitions [21,22]. In order to achieve a society that uses primarily renewable energy sources, [23] stressed the significance of a "hydrogen economy," which incorporates low-carbon hydrogen in various net-zero emissions scenarios. Policymakers are, therefore, taking an interest in hydrogen because it has the potential to work together with other low-carbon technologies to alleviate the effects of climate change [24]. The decarbonization of home cooking and heating could also be aided by hydrogen-fuelled appliances [25,26] and other technologies like induction hobs and heat pumps [21,27].

The various stakeholder groups that may be affected by the hydrogen industry, either directly or indirectly, have different public perceptions, knowledge, opinions, attitudes, and eventual acceptance [28]. For instance, policymakers may support hydrogen, but the community may oppose the installation of infrastructure and plants, and consumers may have concerns about the safety or cost of using hydrogen. Put differently, depending on the market, community, and socio-political acceptance, hydrogen acceptance may differ [29]. Concerns about public opinion of hydrogen energy systems and methods for gaining social support in practice going forward are common among stakeholders and decision-makers [30], as they affect the possibility of socially acceptable hydrogen energy promotion. The "Not In My Back Yard" effect is usually blamed for the "individual gap" that previous research in the field of wind energy has revealed, which denotes the circumstance in which people support wind energy generally but are against a local wind farm in their vicinity [31–33]. Perception studies on HETs are thus essential for understanding consumer behavior and boosting public acceptance of emerging energy technologies like hydrogen [29].

Determinants of preferences, attitudes, and behavior toward the environment are the subject of a plethora of research, and environmental psychology is one field that specializes in studying these factors; energy and transportation are the subjects of most of this research [28]. To plan future research into HETs and to apply the pertinent guidelines to public engagement and communication strategies, it is crucial to review the findings and methodological lessons learned from these studies. A few studies in the past have, therefore, employed the traditional review approach to assess the elements that influence the acceptance or adoption of hydrogen or HETs. Some of these studies include Steller et al. [34], who reviewed the socio-psychological factors affecting the acceptance of HETs. Scovell [35] analyzed data from 27 quantitative studies investigating the connection between HET acceptance and psychological variables. Similarly, [36] reviewed the social, economic, and regulatory issues against the production and use of green hydrogen in the US. Huijts et al. [37] also reviewed the factors influencing public acceptance of HETs in transport. A study by Gordon et al. [38] also reviewed the public's perception of hydrogen homes. Finally, [39] conducted a *meta*-analysis review on the willingness of consumers to buy hydrogen fuel vehicles.

From the reviewed literature presented in the earlier section, it is evident that most review studies on the acceptance or adoption of hydrogen have been conducted using the conventional review approach. There is very little or no information on a review that employs the bibliometric review approach to provide a comprehensive bird's eye view of factors that influence the acceptance or adoption of hydrogen. However, bibliometric review helps identify current patterns in the scholarly literature and provides inspiration and guidance for future research [40,41]. Due to its essential role in the supervision of information and knowledge management, it has gained popularity in information science and can provide a thorough summary and structure for research areas [42]. Numerous bibliometric analyses have been used recently to assess research in various fields, such as accessibility in transportation [43] and resource-based theory in management [44]. Other studies also employed the bibliometric review approach in the following areas: energy storage integrated into a grid system [40], fuel cells [45], hydrogen safety [46], food waste to hydrogen [47], hydrogen electrolyser [48], marine energy [49], and biochar utilization [50].

Currently, there is a lacuna in the literature concerning a bibliometric review on the issues that affect the acceptance of hydrogen among the public or community. All things considered, studies that have already been conducted have examined the variables that influence hydrogen acceptance; however, there is a dearth of worldwide analysis on the evolutionary trend of technical research frontiers and hotspots in the field of hydrogen acceptance, and the reviews as demonstrated supra that exist in this area place more emphasis on the fundamental development of the research topics, which does not provide enough information crucial for determining the future path of hydrogen acceptance and enhancing the HET knowledge system. This study thus fills that research gap by employing both bibliometric and systematic review approaches to evaluate the factors affecting one's willingness to accept hydrogen energy. This study is anticipated to answer the following research questions: RQ1: Between 2003 and 2023, how many projects were involved in hydrogen acceptance research? Global and regional research projects on hydrogen acceptance have been carried out over the last 20 years to address the social, economic, and cultural factors affecting its adoption. This information shows how much work has been done by the public, businesses, and governments to comprehend and promote hydrogen as a fuel. RQ2: What is the current trend in hydrogen acceptance? Understanding the trends can guide future research and policy initiatives, providing insights into successful acceptance-building strategies and areas that need improvement. RQ3: Do any publications, authors, or countries influence the field most? Understanding leading publications, authors, or countries in hydrogen acceptance research helps understand the evolution of hydrogen energy in scientific and public spheres. The influence of trusted voices, authoritative publications, and successful policy models is crucial for increasing societal buy-in and accelerating hydrogen energy acceptance worldwide. This helps target resources, foster collaboration, and prioritize actions. RQ4. Which subjects are the focus of this particular field of study? Determining the focus of hydrogen energy research will aid in the adoption process by identifying and tackling the societal and technological obstacles to hydrogen adoption. RQ5. What is the future of hydrogen acceptance research? This can be achieved by identifying and recommending potential research topics for future studies.

The study is organized as follows: Section 2 provides the materials and methods, and the results and discussion follow in Section 3. The conclusion is also presented in Section 4.

Materials and methods

The multidisciplinary field of bibliometrics blends linguistics, statistics, and mathematics. For bibliometric analysis, journal literature is a trustworthy source of data. Semantic networks are used in knowledge graphs to identify relationships between entities. Knowledge graphs, which illustrate the evolutionary mechanisms, links between studies, and developmental history of research disciplines, can be produced by applying bibliometric methods [22,51]. Compared to databases like the Web of Science (WoS), Scopus includes a broader range of works related to technological topics, making it the preferred reference source for this study [52,53]. ResearchGate and Google Scholar were not included in the analysis because of their poor bibliometric result reliability [54].

The following search queries were used in the Scopus database in conjunction with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Fig. 1) to identify and screen the pertinent literature on the subject matter: TITLE-ABS-KEY (“hydrogen” OR “hydrogen energy” OR “H_2 energy” OR “H_2 gas” OR “hydrogen gas”) AND (“consumer acceptance” OR “community acceptance” OR “household acceptance” OR “social acceptance” OR “public acceptance”). The search period was set to 2003–2023, and the subject area included all areas. Based on this, a total of 307 documents were obtained. The document type was then set to include articles and conference papers, which reduced the documents to 238. The screening process further included documents written solely in the English language, further reducing the number of documents to 233, which were finally retrieved from the Scopus database. A further search through the individual data led to the exclusion of 125 documents that were either out of scope or incomplete. A total of 108 documents were therefore found to be relevant to the course of study and were thus used for the analysis.

Results and discussion

This section presents and comprehensively discusses the findings obtained from the bibliometric analysis. The following sections are discussed: (i) overview of bibliometric data, (ii) distribution of published articles, (iii) geographical distribution of articles, (iv) keywords and trend topics, most relevant institutions and top cited countries and a review of the most relevant top cited papers.

Overview of bibliometric data

Fig. 2 summarizes the bibliometric data over 19 years from 2004 to 2023. Note that the search included the year 2003. However, upon screening, there was no pertinent data on the topic for that year. It can be seen that a total of 108 documents were produced from 57 sources. The field has shown steady growth, evidenced by the 5.3 % annual growth rate. This growth indicates increasing interest and investment in hydrogen energy acceptance research. The involvement of 350 authors, with an average of 3.56 co-authors per document, suggests a collaborative approach to studying this complex topic. The international co-authorship rate of 12.96 % points to some global cooperation, though there may be room for more cross-border collaborations to tackle this globally relevant issue. The presence of 15 authors of single-authored documents indicates that some researchers are also pursuing independent work, possibly providing unique perspectives. The substantial number of references implies a thorough grounding of the research in

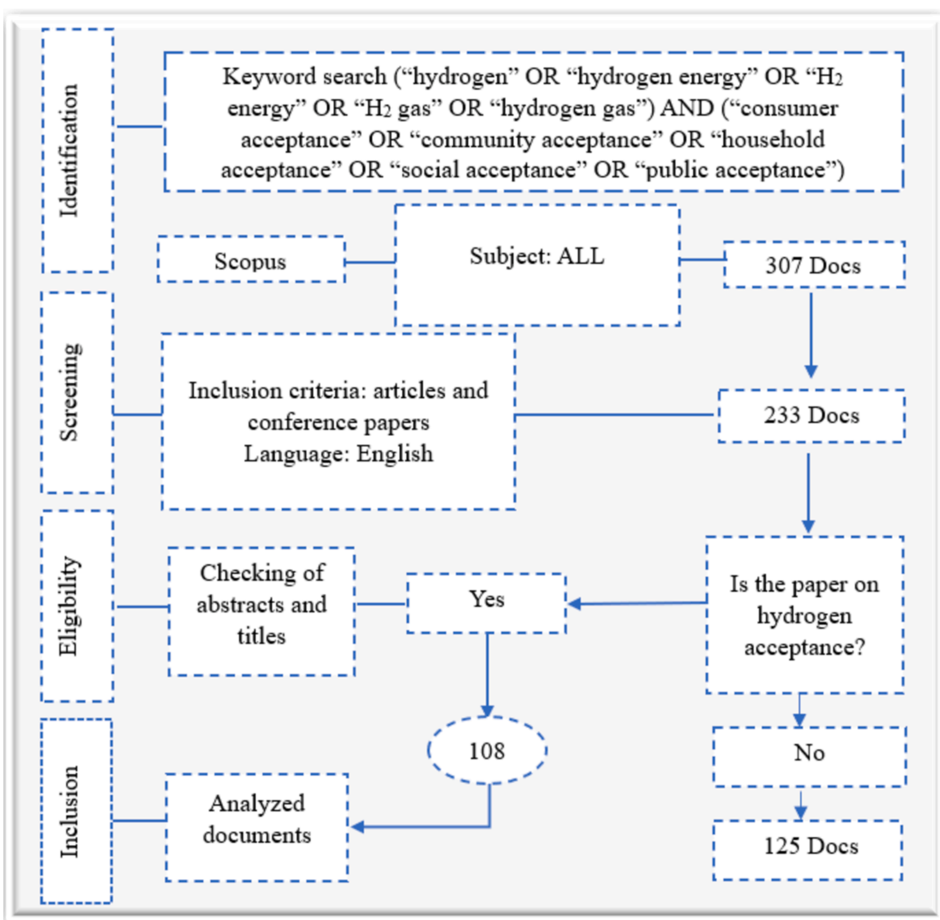

Fig. 1. The PRISMA method used in the analysis.

Fig. 2. Summary of bibliometric data.

existing literature. At the same time, the average document age of 8.59 years suggests that the field is building on relatively recent knowledge. The average of 34.8 citations per document indicates that the research is impactful and widely referenced within the scientific community. The 332 author's keywords highlight the different subtopics and approaches within the field of hydrogen energy acceptance. These metrics collectively imply a growing, collaborative, and impactful research area. The results suggest that the scientific community actively understands and addresses the challenges of hydrogen energy acceptance, which is crucial for the transition to cleaner energy sources. The collaborative nature of the research indicates a multidisciplinary approach, which is essential for tackling the complex technological, economic, social, and policy aspects of hydrogen energy adoption. However, the relatively modest international co-authorship rate suggests there is potential for more global collaboration to share insights and best practices across different contexts. The high citation rate implies the research is influential and will likely inform policy decisions and further studies.

Annual distribution of published articles

All articles published between 2004 and 2023 are shown in Fig. 3. It can be examined that there is a noticeable fluctuation in the number of articles published each year, with some years showing significant spikes and others experiencing notable dips. The year 2004 started with 6 articles, followed by a decrease to 2 in 2005. The publication count then oscillated between 1 and 7 articles per year until 2017, with notable peaks in 2006, 2008, and 2010 (7 articles each) and a complete absence

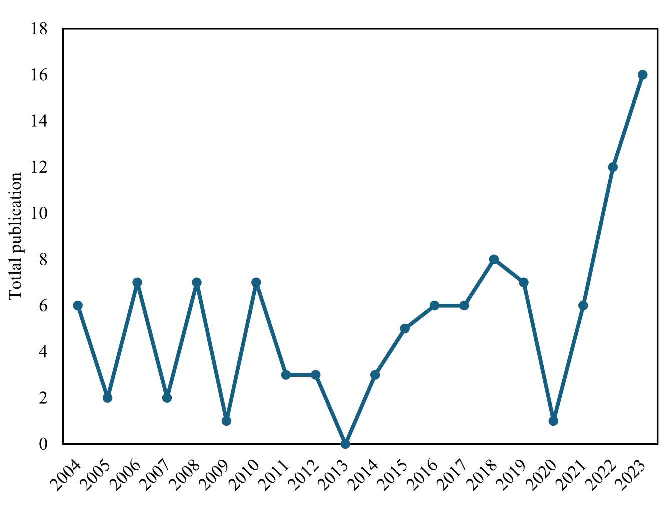

Fig. 3. Yearly publication output.

of publications in 2013. From 2015 to 2019, there was a relatively consistent output ranging from 5 to 8 articles annually, suggesting a growing and sustained interest in the topic. However, 2020 saw a sharp decline to just 1 article, possibly due to the global COVID-19 pandemic affecting research activities. The most striking feature of the figure is the significant upward trend in the last three years, with 6 articles in 2021, doubling to 12 in 2022 and reaching a peak of 16 in 2023. This recent surge implies a rapidly growing interest in hydrogen energy acceptance factors, possibly driven by an increasing global focus on sustainable energy solutions and decarbonization efforts. Despite yearly fluctuations, the overall trend shows a general increase in research output on this topic over the two decades. This growing body of literature suggests an evolving understanding of hydrogen energy adoption's complexities, potentially informing policy decisions, technological developments, and public engagement strategies. The recent acceleration in publications may indicate that hydrogen energy is gaining more attention as a viable alternative to cleaner energy sources, with researchers increasingly exploring the social, economic, and technical factors that influence its acceptance. This trend could have significant implications for energy policy, infrastructure development, and public perception of hydrogen as an energy carrier.

Geographical distribution of research publications and collaborations

The frequency of publications across various countries is shown in Fig. 4. Japan leads with 68 publications, followed by Germany with 48 and China with 44. The United Kingdom and the United States ranked in the top five with 33 and 24 publications, respectively. This distribution suggests that developed economies with strong technological and industrial bases are heavily invested in hydrogen energy research. The prominence of Japan, Germany, and China, in particular, may reflect their national strategies to transition towards cleaner energy sources and reduce carbon emissions. European countries feature prominently, with Portugal, Netherlands, Spain, France, Norway, and others contributing significantly, which could indicate the European Union's collective push towards sustainable energy solutions.

The presence of emerging economies like India, Turkey, and Malaysia in the top ranks suggests a growing global interest in hydrogen energy, potentially driven by the need to address energy security and environmental concerns. The varied representation of countries, from large industrialized nations to smaller ones like Iceland and Singapore, implies that hydrogen energy acceptance is a topic of global relevance, transcending geographical and economic boundaries. However, the disparities in publication frequencies also highlight potential gaps in research capacity or prioritization among different nations. Countries with fewer publications, such as Australia, Mexico, and Switzerland, may need to increase their research efforts to keep pace with global developments in hydrogen energy acceptance. The overall distribution

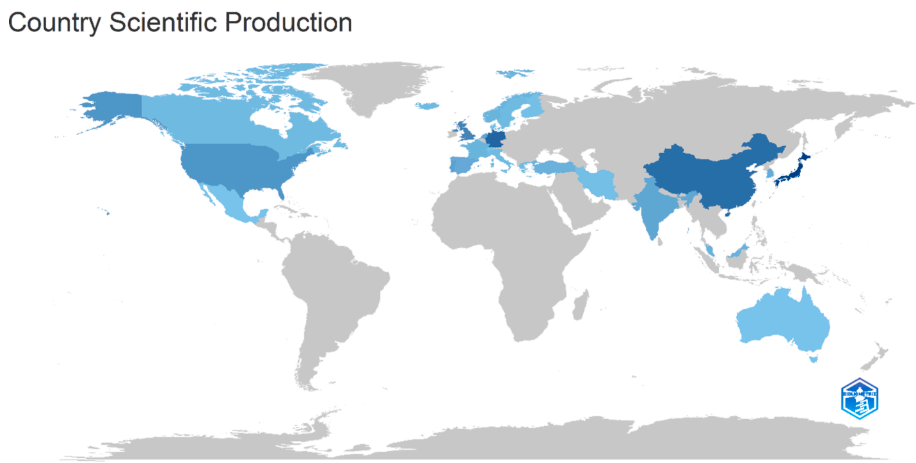

Fig. 4. Country-wise contribution.

of research output could significantly affect the global adoption of hydrogen energy technologies. Countries leading in research may gain competitive advantages in technology development, policy formulation, and market readiness for hydrogen-based solutions. This could influence international collaborations, technology transfer, and the shaping of global standards for hydrogen energy implementation.

Many countries worldwide are making significant strides in developing coupled electricity and hydrogen markets, a strategic approach aimed at accelerating the decarbonization of energy systems [55,56], achieving decarbonization goals and transforming the global energy sector [57]. Integrating renewable energy sources (RES) with hydrogen production is crucial to achieving carbon neutrality. By linking RES with hydrogen producers, these markets can efficiently balance supply and demand, enabling the generation of green hydrogen at scale while optimizing the use of fluctuating renewable energy. This joint operation has the potential to transform contemporary energy markets, offering greater flexibility, energy storage capabilities, and a pathway to decarbonize hard-to-abate sectors such as heavy industry and transport [58]. The development of such coupled markets is already being advanced in regions such as Europe and Asia, where policy frameworks and investments are aligning to support the expansion of hydrogen as an essential energy carrier, further facilitating the transition to low-carbon energy systems. For instance, Japan is at the forefront, investing heavily in hydrogen as part of its energy strategy. The government has allocated significant funds, including $2.7 billion for developing large-scale hydrogen supply chains and $700 million for hydrogen generation projects. Japan's approach includes fostering a robust regulatory environment to attract investments in hydrogen technologies [59].

Likewise, India is also emerging as a key player, with a $2 billion incentive program aimed at becoming Asia's leading hydrogen exporter. The Indian government is leveraging low-carbon solutions and has established partnerships with Australia to enhance hydrogen cooperation [59]. Countries like Germany, the Netherlands, and France are leading European hydrogen production efforts, collectively accounting for a significant portion of the continent's capacity. As of late 2022, Europe had 476 operational hydrogen production facilities with a cumulative capacity of approximately 11.30 million tons annually [60]. The integration of hydrogen into the electricity market is facilitated through extensive infrastructure, including dedicated pipelines and refueling stations for fuel cell vehicles [60].

On the other hand, Africa is witnessing a surge in proposed hydrogen projects, particularly in Morocco and Egypt, which are seen as potential hubs for renewable hydrogen due to their vast RES. However, many projects remain conceptual without binding agreements or financial commitments [61]. The focus on exporting hydrogen adds complexity, as countries must compete with technologically advanced nations while addressing infrastructure challenges.

Fig. 5 depicts the countries' collaboration map. Biblioshiny's country-level collaboration map is a tool that shows how nations interact in a particular field of study, highlighting key players, new research centers, regional alliances, and strategic partnerships. Stakeholders can use this analysis to understand better how research on hydrogen energy acceptance has developed globally and make well-informed decisions about collaboration. The world's most prominent and active research networks are highlighted on the map. Smaller nodes or less collaborative nations might be signs of new research centers, possibly new competitors, or highly invested nations with weak international networks for collaboration [62].

The map shows varying levels of collaboration intensity among different countries, indicated by various shades of blue, with darker shades likely representing higher levels of research collaboration. The United States, China, and several European countries appear to be key players in this research field, as evidenced by their darker blue coloration. This suggests these nations are at the forefront of hydrogen energy acceptance studies, potentially due to their advanced technological capabilities, research infrastructure, and policy focus on sustainable energy solutions. The map also highlights significant international collaborations, represented by the lines connecting different countries.

Notable collaboration links are visible between the United States and Europe and between the US and China. These connections imply a robust exchange of knowledge, expertise, and resources across continents, crucial for advancing global understanding of hydrogen energy acceptance. Participation of nations from various continents, including North America, Europe, Asia, and Australia, indicates the global nature of this research topic and its relevance to diverse economic and geographical contexts. However, the map also reveals potential gaps in the research network, particularly in Africa and South America, which appear to have limited involvement in these collaborative efforts. This disparity could have implications for the global adoption of hydrogen energy technologies, as region-specific factors affecting acceptance may be underrepresented in the current body of research. The strong collaborative links between developed economies suggest they may set the agenda for hydrogen energy research and potentially influence global standards and policies. This collaboration pattern has implications for technology transfer, policy harmonization, and the potential for creating globally applicable solutions for hydrogen energy acceptance. However, it also raises questions about the inclusivity of this research network and whether the findings can be universally applied across different socio-economic and cultural contexts. The map emphasizes how critical international collaboration is to tackling the intricate issues surrounding the adoption of hydrogen energy, including technological, economic, social, and environmental factors. These collaborative efforts are likely

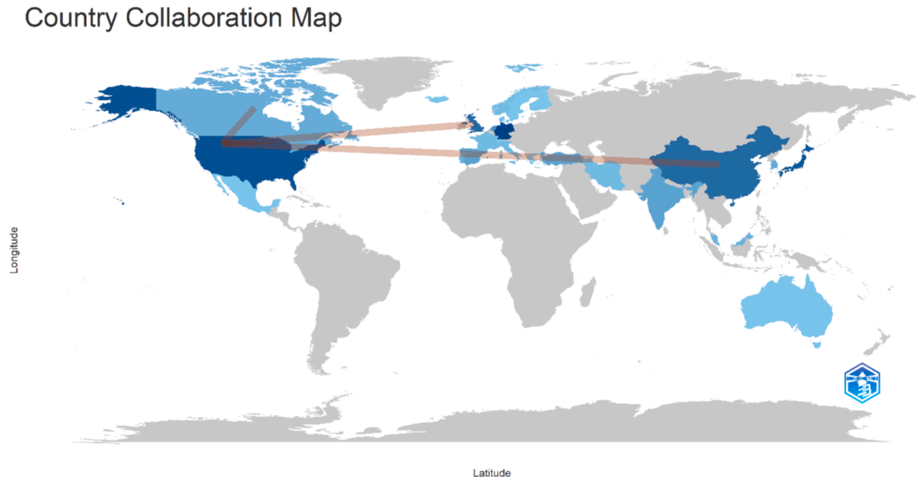

Fig. 5. Country-wise collaboration.

to accelerate innovation, facilitate the sharing of best practices, and potentially lead to more rapid advancements in overcoming barriers to hydrogen energy adoption worldwide.

Fig. 6 displays the single country publications (SCP) and multiple country publications (MCP) for various countries. Japan has the highest number of SCPs, followed by Germany. China stands out with a balanced approach, having 6 SCPs and 4 MCPs, suggesting a strong domestic research base and significant international collaborations. The United Kingdom, USA, India, and Korea focus on domestic research with 6, 5, 4, and 4 SCPs, respectively, but no MCPs, potentially indicating a more nationalized approach to hydrogen energy acceptance research. Turkey, the Netherlands, and Portugal demonstrate a mix of domestic and international collaborations. Malaysia is the only country with MCPs exclusively, suggesting that its research in this area is primarily conducted through international partnerships. Several countries, including Iran, Italy, Norway, Spain, Australia, Canada, Denmark, Finland, and France, have limited but exclusively domestic publications. This result implies varying levels of research intensity and collaboration patterns across countries. The implications of these results are significant. For instance, countries with high numbers of SCPs, like Japan and Germany, maybe developing country-specific insights and solutions, while those with more MCPs, like China, are likely benefiting from diverse international perspectives. The lack of MCPs in many countries suggests potential opportunities for increased international collaboration to enhance global understanding of hydrogen energy acceptance factors. Countries with fewer publications might need to intensify their research efforts to keep pace with global developments in this crucial area of sustainable energy.

Analysis of keywords and trend topic

The word cloud presented in Fig. 7 visually signifies the crucial factors and concepts influencing the acceptance of hydrogen energy. Biblioshiny's word cloud is a potent tool that visually represents scholarly literature by summarizing important research topics and trends. It helps find possible research gaps, track new trends, and

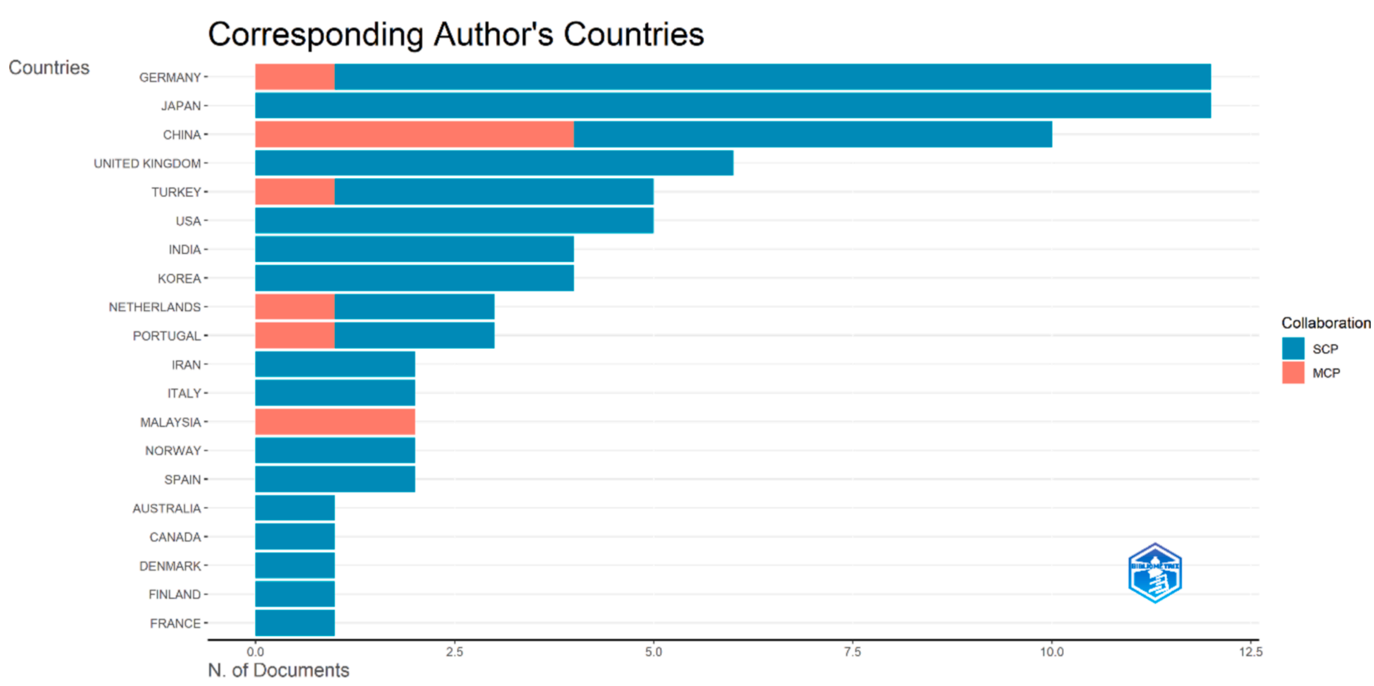

Fig. 6. Corresponding authors' countries.

Fig. 7. Word cloud of author keywords.

identify key focus areas. Researchers can use this information to direct future research investments and strategies, like encouraging the use of hydrogen energy. It can be observed that the most prominent terms are "public acceptance" and "hydrogen," indicating that public perception and understanding of hydrogen technology are central to its adoption and implementation. This emphasis on public acceptance highlights the critical role that societal attitudes and behaviors play in successfully transitioning to hydrogen-based energy systems. Other significant terms like "sustainability," "hydrogen safety," "technology acceptance," and "hydrogen economy" emphasize the diverse nature of the challenges and considerations surrounding hydrogen energy adoption. The presence of "sustainability" suggests that environmental concerns and long-term viability are key drivers in the push for hydrogen energy [63–65].

In contrast, "hydrogen safety" indicates the importance of addressing public concerns about the perceived risks associated with hydrogen use. The inclusion of terms such as "transportation," "hydrogen fueling station," and "hydrogen vehicle" points to the transportation sector as a major focus area for hydrogen energy applications, likely due to its likely to significantly decrease carbon emissions in this sector [66–68]. The appearance of "renewable energy" and "green hydrogen" in the word cloud indicates a strong connection between hydrogen energy and broader sustainable energy goals, highlighting hydrogen's importance in the switch to clean energy. Technical terms like "electrolysis," "fuel cell," and "energy storage" highlight the technological aspects that are crucial for the implementation and development of hydrogen energy systems. The presence of "social acceptance" alongside "public perception" and "risk perception" further emphasizes the importance of addressing societal concerns and fostering positive attitudes towards hydrogen technologies. Economic considerations are represented by terms such as "hydrogen economy" and "sustainable value," suggesting that economic viability and potential benefits are significant factors in the acceptance of hydrogen energy. The inclusion of "policy" and "risk assessment" indicates the importance of regulatory frameworks and thorough evaluation of potential hazards in promoting hydrogen energy adoption. The different terms in the word cloud, from technical to social and economic considerations, demonstrate the complex and interdisciplinary nature of factors affecting hydrogen energy acceptance. This complexity implies that a holistic approach, addressing technological, social, economic, and policy aspects, is necessary to successfully integrate hydrogen energy into existing energy systems. The prominence of public-related terms suggests that engaging with and educating the public about hydrogen energy will be crucial for its widespread acceptance and adoption, highlighting the need for effective communication strategies and public outreach programs in the hydrogen energy sector.

The trend topics in Fig. 8 show the emergence and progression of key themes in this field. Notably, the term "hydrogen" appears as early as the timeline, around 2012, indicating it is a foundational concept in the research. This suggests that initial studies were broadly focused on hydrogen as a potential energy source. Moving forward, more specific and refined topics emerged. "Hydrogen safety" appears next, around 2014, highlighting the growing concern and research focus on addressing safety issues associated with hydrogen technologies – a critical factor in public acceptance. The prominence of "public acceptance" as a research topic appeared around 2016 with the largest circle size, highlighting its paramount importance in the field. This suggests a significant shift in research focus towards understanding and addressing societal perceptions and attitudes towards hydrogen energy. The appearance of "social acceptance" later in the timeline, around 2020, further reinforces this trend, indicating a more comprehensive exploration of the social dimensions of hydrogen energy adoption.

In addition, "hydrogen energy" and "sustainability" appear to be the most recent topics emerging around 2022. This could imply a renewed focus on the broader energy applications of hydrogen and its role in sustainable development, possibly driven by increasing global emphasis on clean energy transitions and climate change mitigation. The varying sizes of the circles in Fig. 8, representing term frequency, provide additional insights. The larger circle for "public acceptance" compared to other terms suggests it has been a dominant theme in recent years, receiving significant attention from researchers. This emphasis on public acceptance implies a growing recognition of the vital role that social factors play in the successful implementation of hydrogen energy technologies. The overall trend depicted in this figure has several implications for hydrogen energy research and implementation. Firstly, it highlights the shift from purely technical considerations (represented by an early focus on hydrogen) to a more holistic approach incorporating safety, public perception, and sustainability. This evolution suggests that researchers and policymakers are increasingly aware of the several challenges in promoting hydrogen energy adoption. The recent emergence of sustainability as a key topic also indicates a growing alignment of hydrogen energy research with broader sustainable development

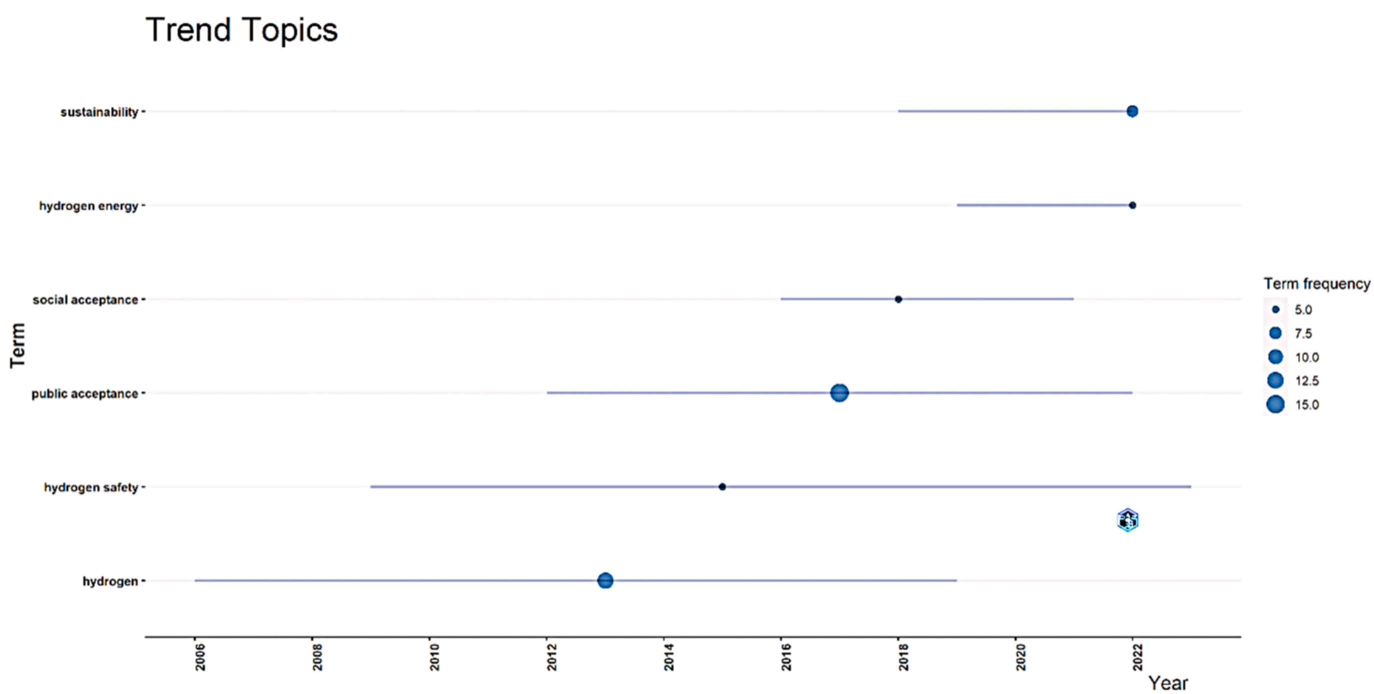

Fig. 8. Trend topics within the field.

goals. Furthermore, the persistent presence of safety-related topics throughout the timeline emphasizes the importance of addressing and communicating the safety aspects of hydrogen technologies to gain public trust and acceptance. The trend towards social and public acceptance topics in recent years implies that future research, policy-making, and implementation strategies for hydrogen energy will likely

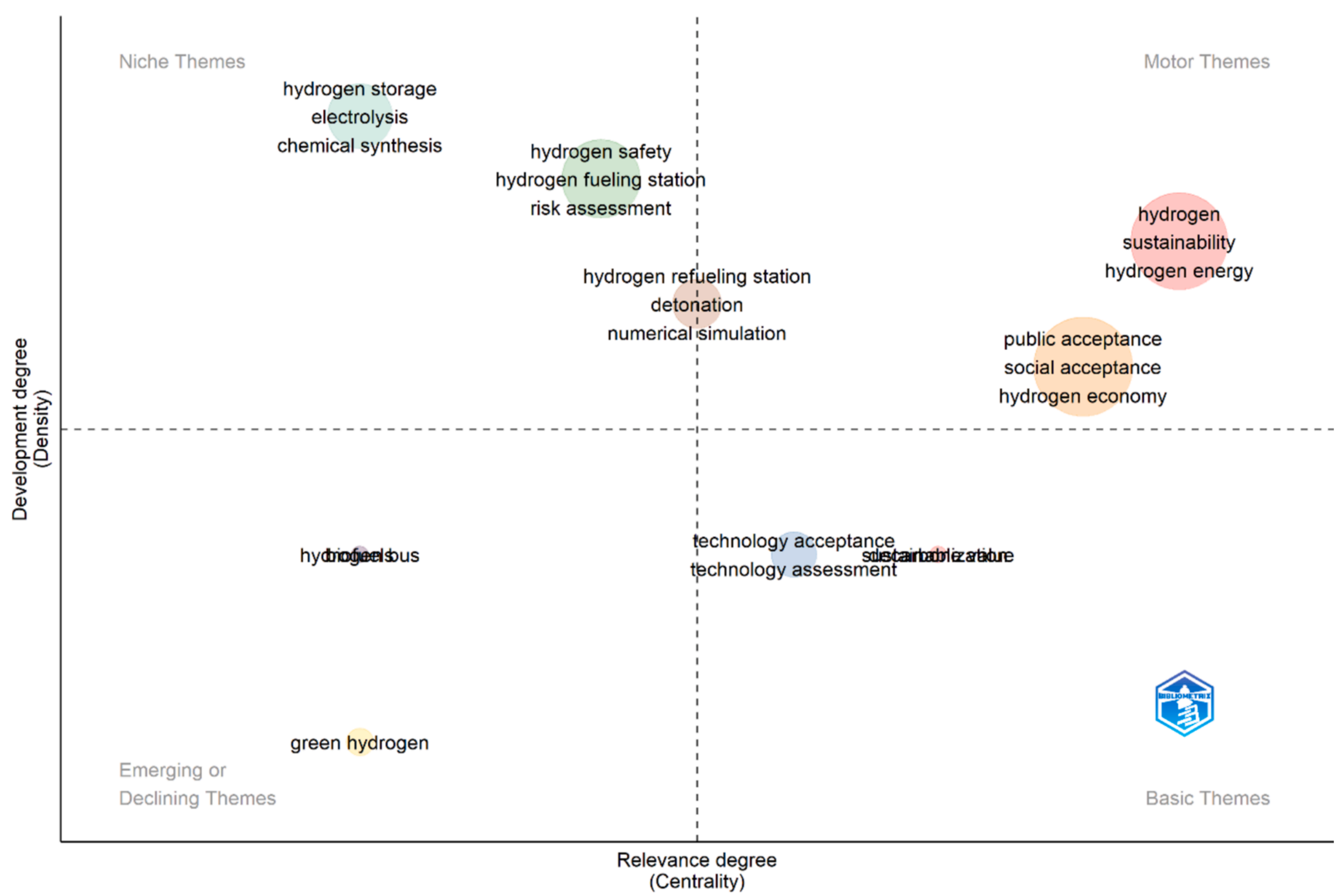

Fig. 9. Thematic map of keywords.

need to strongly emphasize public engagement, education, and addressing societal concerns to ensure the successful adoption of hydrogen energy technologies.

Conceptual structure

This section provides a comprehensive conceptual structure analysis, employing various techniques, including thematic mapping, thematic evolution analysis, factorial analysis, and co-occurrence analysis.

Thematic mapping

The thematic mapping in Fig. 9 shows several key insights across four quadrants: basic themes, motor themes, niche themes, and emerging or declining themes. It can be observed that the basic themes quadrant comprises "technology acceptance," "technology assessment," and "standardization," indicating these are fundamental aspects with high relevance but lower development. The motor themes quadrant, representing highly developed and central topics, includes "hydrogen sustainability," "hydrogen energy," "public acceptance," "social acceptance," and "hydrogen economy." This suggests that sustainability, energy applications, and societal factors are driving the discussion and development of hydrogen acceptance. The niche themes quadrant, showing highly developed but less central topics, includes "hydrogen storage," "electrolysis," "chemical synthesis," "hydrogen safety," "hydrogen fueling station," "risk assessment," "hydrogen refueling station," "detonation," and "numerical simulation." These represent specific technical and safety-related aspects that are well-developed but perhaps more specialized. In the emerging or declining themes quadrant, "green hydrogen" and "hydrogen bus" indicate that newer concepts are gaining attention or potentially declining relevance. The positioning of themes provides essential observations into the current state of hydrogen energy acceptance research and development. The prominence of sustainability, energy applications, and public/social acceptance in the motor themes suggests that these are the primary drivers and concerns in the field.

Meanwhile, the technical aspects of the niche themes indicate a strong focus on practical implementation and safety considerations. The presence of "green hydrogen" as an emerging theme aligns with the growing emphasis on environmentally friendly hydrogen production methods. This thematic map implies that while technical challenges and safety concerns are being actively addressed, the broader acceptance of hydrogen energy heavily depends on its perceived sustainability, economic viability, and social acceptance. The results suggest that future efforts in promoting hydrogen energy should focus on enhancing public understanding, demonstrating economic benefits, and emphasizing sustainability while continuing to refine the technical and safety elements. The results also highlight the need for interdisciplinary approaches, combining technological advancements with social sciences to address the complex factors influencing hydrogen energy acceptance.

Thematic evolution analysis

Fig. 10 displays the thematic evolution of keywords divided into three periods: 2004 – 2012, 2014 – 2019 and 2020 – 2023. In the earliest period (2004–2012), the sole prominent theme was "hydrogen," indicating a broad, generalized interest in the field without specific subtopics dominating discussions. The middle period (2014–2019) shows a marked diversification of themes, introducing "chemical synthesis," "technology acceptance," "public acceptance," "survey," and "energy storage" as key areas of focus. This expansion suggests a shift towards more specialized and practical concerns, comprising technical aspects (chemical synthesis, energy storage) and social dimensions (technology acceptance, public acceptance). The use of surveys during this period

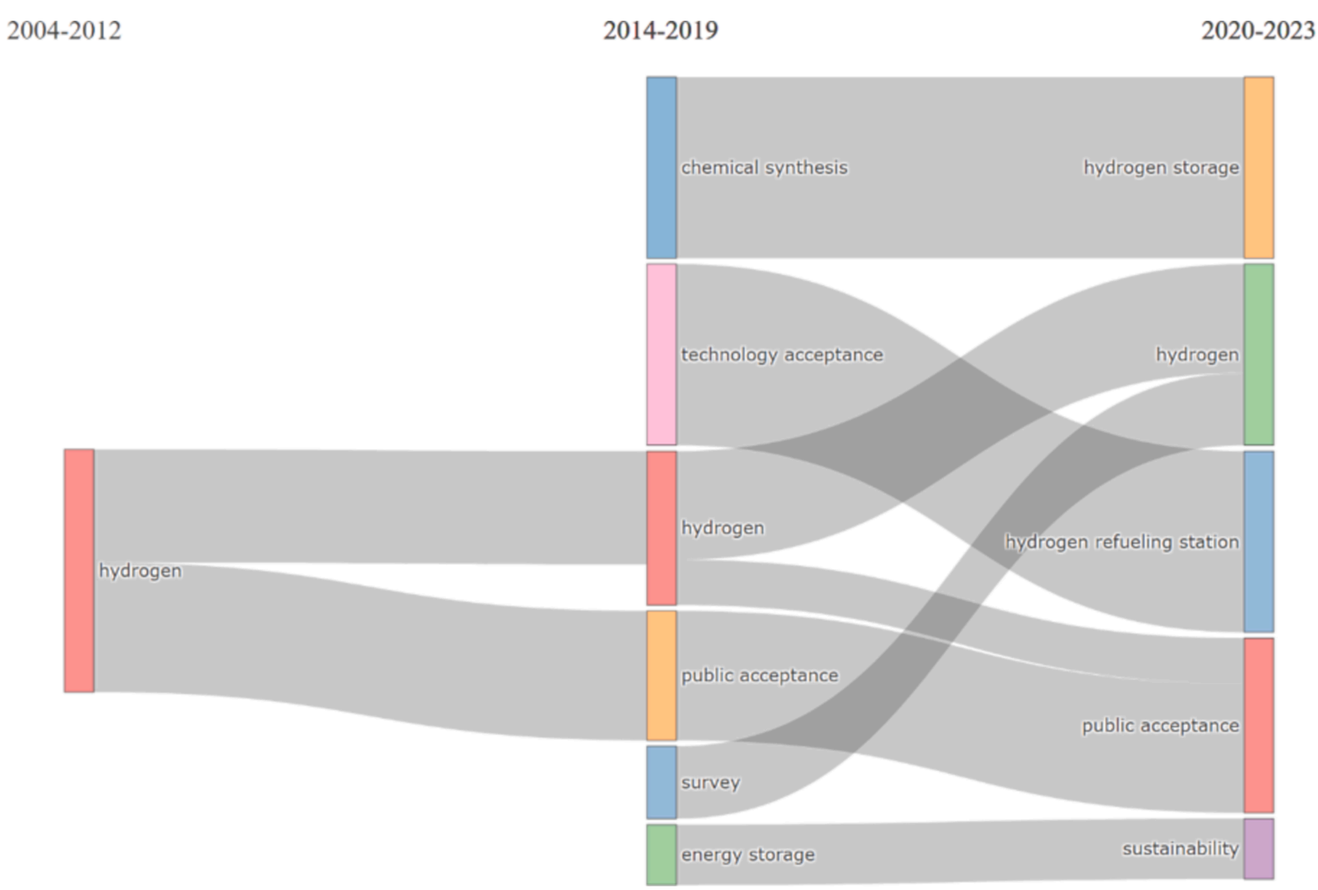

Fig. 10. Thematic evolution of keywords.

implies an increased emphasis on gathering empirical data on public perceptions and attitudes.

The most recent period (2020–2023) demonstrates further evolution and refinement of research themes. "Hydrogen storage" is a prominent topic, indicating the importance of addressing practical challenges in hydrogen implementation. The continuation of "hydrogen" as a theme suggests ongoing broad interest, while "hydrogen refueling station" indicates a focus on infrastructure development for practical application. "Public acceptance" remains a key theme, emphasizing the persistent importance of social factors in hydrogen energy adoption. The emergence of "sustainability" as a new theme in this period aligns with a growing global emphasis on environmental concerns and sustainable energy solutions.

This thematic evolution implies several key trends and implications for hydrogen energy acceptance research and policy. First, there is a clear progression from general interest to more specific, practical concerns, suggesting that the field is maturing and moving closer to real-world implementation. The consistent presence of public acceptance themes across periods highlights the recognition that technological advancement alone is insufficient for successful adoption; social acceptance is crucial. The emergence of sustainability as a theme in the most recent period may indicate a shift in framing hydrogen energy as an alternative energy source and a key component of broader sustainability efforts.

The evolution also suggests a need for increasingly interdisciplinary approaches, combining technical research (e.g., on storage and refueling infrastructure) with social science methodologies (surveys, acceptance studies) and environmental considerations (sustainability). For policymakers and industry stakeholders, this evolution implies that successfully promoting and implementing hydrogen energy technologies will require addressing a complex interplay of technical, social, and environmental factors. Future research and development efforts may need to focus on integrating these diverse aspects, potentially through holistic studies considering the entire lifecycle and societal impact of hydrogen energy systems. Additionally, the persistent focus on public acceptance suggests a continued need for public engagement, education, and transparent communication about the benefits and challenges of hydrogen energy to foster broader societal support.

Factorial analysis

The factorial analysis in Fig. 11 shows a complex interplay of technological, societal, and energy-related themes. The conceptual structure map, created using the multiple correspondence analysis method, displays a triangular distribution of keywords, suggesting three main dimensions influencing hydrogen energy acceptance. The triangle's apex comprises "technology assessment" and "technology acceptance" closely positioned, indicating a strong relationship between evaluating hydrogen technologies and their subsequent acceptance. This proximity implies that thorough and transparent assessment processes are pivotal for fostering public and stakeholder acceptance of hydrogen energy solutions. The importance of these terms at the top of the map suggests they are vital in shaping perceptions and decisions regarding hydrogen energy adoption.

Moving down the right side of the triangle, "hydrogen energy" is positioned higher than other specific applications, suggesting its central role as a broader concept comprising various hydrogen-based technologies. This placement indicates that the overall perception of hydrogen as an energy carrier is a significant factor in its acceptance. Towards the triangle's base, more specific applications and technologies cluster together. Terms like "electric vehicle," "hydrogen fuel cell," "fuel cell," and "energy" are grouped closely, indicating a strong association between hydrogen energy acceptance and its applications in transportation and general energy systems. This clustering suggests that public acceptance and perception of hydrogen energy are closely tied to its practical applications, particularly in familiar contexts like vehicles and power generation.

The distribution of keywords, with some tightly clustered and others more dispersed, implies varying degrees of conceptual relatedness. The

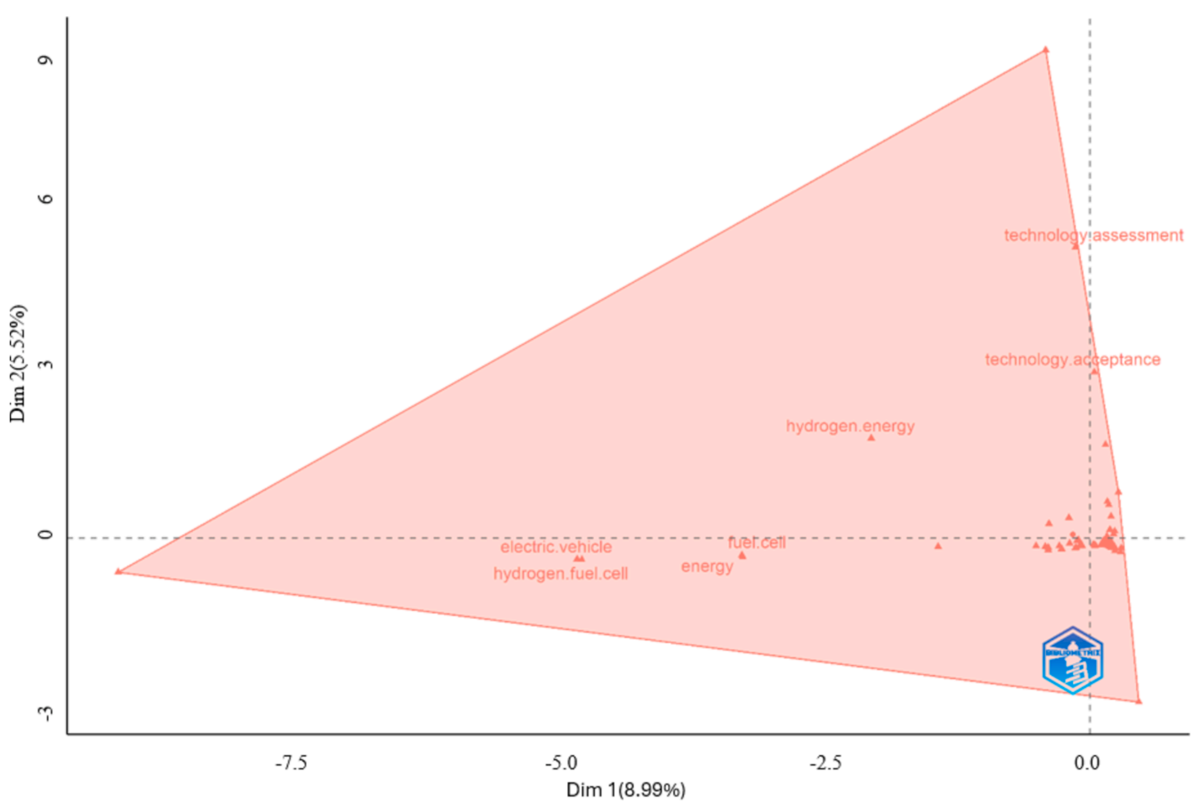

Fig. 11. Factorial analysis of keywords.

tight clustering of some terms suggests that certain aspects of hydrogen energy acceptance are closely interconnected and may need to be tackled holistically. Conversely, the dispersion of other terms indicates that hydrogen energy acceptance is a complex issue with several affecting factors. The implications of this factorial analysis are significant for policymakers, researchers, and industry stakeholders. Firstly, it highlights the importance of comprehensive technology assessment processes that evaluate technical feasibility and consider societal impacts and acceptance factors. Secondly, the analysis suggests that efforts to promote hydrogen energy acceptance should focus on the overarching concept of hydrogen as an energy carrier and its specific applications, particularly in transportation and energy systems. The close association of hydrogen with electric vehicles and fuel cells implies that advancements and public perception in these areas could significantly influence overall hydrogen energy acceptance.

Furthermore, the analysis indicates that a multi-pronged approach is necessary to address the factors influencing hydrogen energy acceptance. This could involve targeted public education campaigns, transparent communication about technology assessments, and demonstrations of practical applications to bridge the gap between abstract energy concepts and tangible benefits. The factorial structure also suggests that strategies for promoting hydrogen energy should be flexible and capable of simultaneously addressing both the broad conceptual aspects and specific technological applications.

Co-occurrence network analysis

Fig. A1 displays the co-occurrence network of keywords. It can be observed that the center of the network contains "hydrogen" as the primary node, indicating its central role in the field. This central position is logical, given that hydrogen is the core subject around which all other factors revolve. Branching out from this central node, the study observes several distinct clusters, each representing a different aspect of hydrogen energy acceptance. The largest and most prominent cluster is centered around "public acceptance," which is depicted as a major node nearly equal in size to "hydrogen." This prominence highlights the critical importance of societal factors in adopting and implementing hydrogen energy technologies. Connected to this cluster are terms like "public perception," "risk perception," and "hydrogen economy," suggesting that public acceptance is closely tied to individuals' perceptions of the risks and economic implications of hydrogen energy.

Another significant cluster revolves around "sustainability," which is closely linked to "hydrogen energy." This cluster includes terms like "transportation" and "fuzzy ahp" (likely referring to the Analytic Hierarchy Process, a decision-making methodology), indicating that sustainability considerations are a key factor in the acceptance of hydrogen, particularly in the transportation sector. The presence of "fuzzy ahp" suggests that complex, multi-criteria decision-making processes are being employed to evaluate the sustainability aspects of hydrogen energy. A smaller but distinct cluster focuses on the technical aspects of hydrogen, including "hydrogen storage," "electrolysis," "chemical synthesis," and "hydrogen utilization." This cluster highlights the importance of technological advancements and practical implementation challenges in shaping the acceptance of hydrogen energy. The network also shows a separate node for "technology acceptance" and "technology assessment," positioned somewhat apart from the other clusters. This positioning suggests that while these factors are essential, they may be considered overarching concepts that apply to evaluating and adopting hydrogen technologies across various domains.

The co-occurrence network analysis has several implications. Firstly, it emphasizes that public acceptance is not just one factor among many but a central and complex issue deeply intertwined with perceptions of risk, economic considerations, and broader societal impacts. This suggests that efforts to promote hydrogen energy should prioritize public engagement, education, and transparent communication about the benefits and potential risks. Secondly, the strong link between hydrogen and sustainability indicates that environmental considerations are vital to acceptance. This implies that positioning hydrogen as a sustainable energy solution, particularly in sectors like transportation, could be an effective strategy for increasing its acceptance. Technical terms in a distinct cluster suggest that while technological aspects are important, they may not be the primary driver of public acceptance. Instead, they appear to be a necessary but insufficient condition for widespread adoption. This implies that technical advancements should be pursued in tandem with efforts to address public perceptions and sustainability concerns. The network structure also highlights the interconnected nature of these factors, suggesting that a holistic approach is necessary when addressing hydrogen energy acceptance. Policymakers, researchers, and industry stakeholders should consider how interventions or advancements in one area (e.g., improving storage technology) might impact other factors (e.g., public perception of safety).

Most relevant institutions' analysis

Fig. A2 displays the leading institutions researching factors affecting the acceptance of hydrogen energy, as indicated by the number of articles published. The Laboratório Nacional de Energia e Geologia (National Laboratory of Energy and Geology) in Portugal has the highest publications with 16 articles. This is followed by the National Institute for Fusion Science in Japan, with 11 articles highlighting Japan's significant interest in hydrogen as a potential energy source. China's Hefei University of Technology and Japan's Yokohama National University are tied for third place with 10 articles each, further emphasizing the prominence of Asian institutions in this field. Bahcesehir University in Turkey comes next with 9 articles.

The Research Institute of Science for Safety and Sustainability, likely based in Japan, follows with 8 articles emphasizing the importance of safety considerations in hydrogen energy adoption. Universiti Teknologi Malaysia's 7 articles demonstrate Malaysia's engagement in this research area. The presence of Cranfield University (UK), with 6 articles, and Chalmers University of Technology (Sweden), with 5 articles, shows European involvement in hydrogen energy acceptance studies. The Energy Technology Research Institute, tied with Chalmers at 5 articles, rounds out the top ten.

These results imply a global interest in hydrogen energy acceptance, with a notable concentration of research efforts in Asia and Europe. The different institutions suggest that hydrogen energy is being explored from various perspectives, including technological, safety, and societal aspects. The number of articles from these institutions indicates a growing body of knowledge on the factors influencing hydrogen energy acceptance, which could be crucial for policymakers and industry stakeholders in developing strategies for wider hydrogen adoption. The involvement of national laboratories and specialized research institutes alongside universities highlights the multidisciplinary nature of this research area, combining academic inquiry with practical applications and policy considerations. This research, which focuses on multiple countries and institutions, suggests a collective recognition of hydrogen's potential as a key component in future energy systems and the importance of understanding and addressing barriers to its acceptance.

Top cited countries and review of the most relevant top cited papers

The top cited countries are shown in Fig. A3. It can be observed that the United Kingdom leads in total citations with 429, suggesting a significant influence in the field while also maintaining a high average of 71.5 citations per article. This indicates a high volume of research and high-quality, impactful studies. Japan follows closely with 422 total citations but a lower average of 35.2, implying a larger number of publications with varying impact. Germany, ranking third in total citations, shows a similar pattern to Japan, with an average of 27.2 citations per article. Turkey has fewer total citations than the top three but boasts a high average of 60.6, suggesting fewer but highly influential publications. China's total citations are comparable to Turkey's but with a lower average, indicating a larger research volume with moderate impact per article. The Netherlands has the highest average citations per article among the top countries despite having fewer total citations than the leaders, pointing to highly influential research outputs. The United States, while having a respectable total citation count, shows a middling average, suggesting a balanced output in terms of quantity and impact.

Despite having lower total citations, Singapore, Canada, and Iceland show remarkably high average citations, indicating that while their research output may be lower in volume, it has a disproportionately high impact. This could suggest focused, high-quality research programs in these countries. Countries like Korea, Portugal, and Iran show moderate performance in total and average citations, indicating steady contributions to the field. India has a decent total citation count and has one of the lowest average citations. European countries like France, Norway, Spain, Denmark, and Finland show varying patterns, with France having high average citations but lower total citations.

In contrast, others have more modest figures, indicating diverse European research areas. Malaysia shows the lowest figures in both categories, suggesting potential for growth in this research area. These results imply a global interest in hydrogen energy acceptance, with research impact concentrated in certain countries. The variations in total and average citations highlight different research strategies and focus areas across nations, with some prioritizing quantity and others quality of output. This global distribution of research impact accentuates the international nature of hydrogen energy research and the potential for cross-border collaboration to address acceptance factors. The high impact of research from smaller countries like Singapore and Iceland suggests that targeted, specialized research can have a significant influence regardless of a country's size or overall research output. These findings could inform policy decisions on research funding and international collaborations in the field of hydrogen energy acceptance.

Table 1 presents the most relevant cited papers. The studies cover several topics: public perceptions, acceptance, safety concerns, policy impacts, and technological aspects of hydrogen adoption. For instance, Solomon & Banerjee's global survey and Ricci et al.'s critical review on public perceptions are among the most cited works, indicating the importance of understanding societal attitudes towards hydrogen energy. Safety-related research, such as Ng & Lee's study on explosion problems and Mohammadfam & Zarei's risk analysis framework, also feature prominently, emphasizing the critical role of addressing safety concerns in public acceptance. The high citation rates of papers focusing on specific countries or regions, like Itaoka et al.'s study on Japan and Kang & Park's research on Korea, suggest that cultural and geographical contexts significantly influence hydrogen acceptance. More recent studies, such as Gordon et al.'s work on socio-technical barriers and Apostolou & Welcher's examination of hydrogen-based mobility prospects, have received substantial citations in a short time, indicating a growing interest in the practical implementation of hydrogen technologies.

It is worth mentioning that several studies, including those by Ricci et al. [69], Itaoka et al. [70], and Oltra et al. [71], highlighted the gap in public knowledge about hydrogen technologies. Though awareness is generally increasing, a detailed understanding of hydrogen production, storage, and use remains limited. This knowledge gap presents both a challenge and an opportunity for policymakers and industry stakeholders to engage in targeted educational campaigns. Norazahar et al. [72] assessed the factors influencing public acceptance of hydrogen as a vehicle fuel in Malaysia, focusing on socio-demographic factors, environmental awareness, and safety perceptions. Solomon & Banerjee [73] highlighted challenges in large-scale adoption and knowledge gaps in public opinion formation. Schulte et al. [74] emphasized the role of values and perceptions in shaping attitudes.

Safety concerns emerged as a significant factor influencing public acceptance across multiple studies. For example, Gupta et al. [75], Zhiyong et al. [76], and Yu et al. [77] emphasized the need for rigorous safety assessments and effective risk communication to address public

Table 1
Most relevant cited papers.

Author(s)	Title of paper	Total citations	Total citations per year
Solomon & Banerjee [73]	A global survey of hydrogen energy research, development and policy	155	8.16
Ricci et al. [69]	What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence	148	8.71
Schulte et al. [74]	Issues affecting the acceptance of hydrogen fuel	137	6.52
Ng & Lee [102]	Comments on explosion problems for hydrogen safety	115	6.76
Itaoka et al. [70]	Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles	114	14.25
Mohammadfam & Zarei [99]	Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework	98	9.80
Kang & Park [84]	Impact of experience on government policy toward acceptance of hydrogen fuel cell vehicles in Korea	90	6.43
Gupta et al. [75]	Hydrogen related risks within a private garage: Concentration measurements in a realistic full scale experimental facility	82	5.13
Achterberg et al. [95]	Unknowing but supportive? Predispositions, knowledge, and support for hydrogen technology in the Netherlands	80	5.33
Ono & Tsunemi [98]	Identification of public acceptance factors with risk perception scales on hydrogen fueling stations in Japan	69	8.63
(Zhiyong et al. [76]	Quantitative risk assessment on a gaseous hydrogen refueling station in Shanghai	68	4.53
Zimmer & Welkevb[103]	Let's go green with hydrogen! The general public's perspective	56	4.31
Iribarren et al. [1]	Assessing the social acceptance of hydrogen for transportation in Spain: An unintentional focus on target population for a potential hydrogen economy	54	6.00
Sherry-Brennan et al. [104]	Public understanding of hydrogen energy: A theoretical approach	52	3.47
(Zaunbrecher et al. [78]	What is Stored, Why, and How? Mental Models, Knowledge, and Public Acceptance of Hydrogen Storage	49	5.44
Apostolou & Welcher [85]	Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark	44	11.00
Gordon et al. [90]	Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions	44	22.00
Hienuki et al. [79]	How knowledge about or experience with hydrogen fueling stations improves their public acceptance	42	7.00
Ono et al. [96]	Does risk information change the acceptance of hydrogen refueling stations in the general Japanese population?	41	6.83
Chen et al. [81]	The effects of perceived barriers on innovation resistance of hydrogen-electric motorcycles	40	5.71

(continued on next page)

Table 1 (*continued*)

Author(s)	Title of paper	Total citations	Total citations per year
Tarigan et al. [82]	Estimating determinants of public acceptance of hydrogen vehicles and refuelling stations in greater Stavanger	39	3.00
Heinz & Erdmann [93]	Dynamic effects on the acceptance of hydrogen technologies—an international comparison	37	2.18
Han et al. [83]	The public's acceptance toward building a hydrogen fueling station near their residences: The case of South Korea	30	10.00
Al-Amin & Doberstein [105]	Introduction of hydrogen fuel cell vehicles: prospects and challenges for Malaysia's transition to a low-carbon economy	30	5.00
Kar et al. [91]	Hydrogen economy in India: A status review	28	14.00
Bigerna & Polinori [89]	Willingness to Pay and Public Acceptance for Hydrogen Buses: A Case Study of Perugia	26	2.60
Yu et al. [77]	The flame mitigation effect of vertical barrier wall in hydrogen refueling stations	25	8.33
Hienuki et al. [80]	Public acceptance for the implementation of hydrogen self-refueling stations	21	5.25
Oltra et al. [71]	Public acceptance of hydrogen fuel cell applications in europe	19	2.38
Bentsen et al. [86]	5In the green? Perceptions of hydrogen production methods among the Norwegian public	18	9.00
Lee et al. [101]	Evaluating hydrogen risk management policy PR: Lessons learned from three hydrogen accidents in South Korea	15	7.50
Ono et al. [97]	Construction of a structural equation model to identify public acceptance factors for hydrogen refueling stations under the provision of risk and safety information	14	4.67
Liu et al. [94]	Consumer acceptance under hydrogen energy promotion policy: Evidence from Yangtze River Delta	11	5.50
Lee et al. [92]	Public acceptance of hydrogen buses through policy instrument: Local government perceptions in Changwon city	9	4.50
Gordon et al. [38]	Price promises, trust deficits and energy justice: Public perceptions of hydrogen homes	8	4.00
Norazahar et al. [72]	Hydrogen application and its safety: An overview of public perceptions and acceptance in Malaysia	8	4.00
Estrada Poggio et al. [100]	Monitored data and social perceptions analysis of battery electric and hydrogen fuelled buses in urban and suburban areas	5	2.50
Wang et al. [88]	Willingness of Chinese households to pay extra for hydrogen-fuelled buses: A survey based on willingness to pay	5	2.50
Chen & Chen [87]	A Study on Willingness to Pay of Hydrogen Energy and Fuel Cell Technologies	4	0.36
Li et al. [106]	The influence of driver's psychological states on the safety perception of hydrogen electric vehicles	4	0.67
Hoffmann et al. [107]	The value of secure electricity supply for increasing acceptance of green hydrogen First experimental evidence from the virtual reality lab	3	1.50

concerns about hydrogen technologies, particularly in transportation and refueling infrastructure. In addition, Ng and Lee's study on explosion problems stressed the need for further research on hydrogen combustion mechanisms.

Zaunbrecher et al. [78] explored public attitudes and knowledge regarding hydrogen storage technologies within the context of Germany. Hienuki et al. [79] investigated how campaigns to raise public awareness of hydrogen energy technology affect the technology's acceptance. Hienuki et al. [80] evaluated public trust in self-refueling hydrogen stations, comparing it with trust in traditional gasoline stations based on a 300-person online survey of Japanese drivers. Chen et al.[81] analyzed consumer acceptance of hydrogen-electric motorcycles and the factors influencing it, using innovation resistance and environmental concern as key variables. Tarigan et al. [82] examined the intricate connections between public acceptance of hydrogen-powered vehicles and refueling stations, environmental attitudes, and hydrogen knowledge. Han et al. [83] examined South Korea's public opinion on constructing hydrogen filling stations close to homes.

Studies such as those by Kang & Park [84], Apostolou & Welcher [85], and Bentsen et al. [86] consistently showed that the perceived environmental benefits of hydrogen technologies positively influence public acceptance. Green hydrogen, in particular, receives higher support levels than blue or grey hydrogen, highlighting the importance of sustainable production methods in gaining public approval.

Several studies, including Chen & Chen [87], Wang et al. [88], and Bigerna & Polinori [89], explored the economic aspects of hydrogen adoption, such as willingness to pay for hydrogen technologies. These studies revealed that while some are willing to pay a premium for hydrogen technologies, economic incentives and clear cost-benefit demonstrations are crucial for widespread adoption. Gordon et al. [90], Kar et al. [91], and Lee et al. [92] emphasized the importance of supportive policy and regulatory frameworks in facilitating the transition to hydrogen technologies. These studies highlight the need for integrated approaches that address hydrogen adoption's technical, economic, and social dimensions.

Studies conducted across different countries and regions, such as those by Heinz & Erdmann [93], Iribarren et al. [1], and Liu et al. [94], revealed notable differences in the public's perceptions and acceptance of hydrogen-based technologies. These findings emphasize the need for tailored hydrogen promotion and implementation approaches considering local contexts and cultural factors. Achterberg et al. [95] examined cultural inclinations that mediate the relationship between public awareness and adoption of hydrogen technology, such as trust in technology and environmental concerns.

The work of Ono et al. [96], Ono et al. [97] and One & Tsunemi [98] highlighted the critical role of effective risk communication in shaping public acceptance of hydrogen technologies. These studies demonstrate that providing balanced information about risks and benefits can significantly influence public perceptions and acceptance. Mohammadfam & Zarei [99] focus on safety risk analysis and changing public perceptions over time. Estrada Poggio et al. [100] assessed the real-world performance of hydrogen technologies in transportation and provided valuable insights into the current state of technological readiness. These findings help bridge the gap between theoretical potential and practical implementation, offering important data for decision-makers and potential adopters.

Furthermore, other studies, including those by Gordon et al. [38] and Lee et al. [101], highlighted the importance of public trust in government institutions and energy companies in shaping acceptance of hydrogen technologies. Building and maintaining this trust through transparent communication and responsible implementation is crucial in successfully transitioning to hydrogen-based systems.

It is important to mention that the widespread adoption of hydrogen technologies is complex. Although there is mounting recognition of hydrogen's potential as a clean energy carrier, especially in transportation and industry, significant challenges remain. These challenges include addressing safety concerns, improving public understanding, developing supportive policy frameworks, and ensuring economic viability. The synthesis of these studies provides valuable guidance for policymakers, industry leaders, and researchers working towards a hydrogen-based energy transition. As research in this field continues to evolve, ongoing monitoring and assessment of public attitudes, technological advancements, and policy effectiveness will be crucial in guiding the effective incorporation of hydrogen into global energy systems. The collective insights from these studies lay the groundwork for strategic planning and well-informed decision-making in order to pursue a sustainable, hydrogen-inclusive energy future.

Summary of factors influencing hydrogen acceptance and potential future research directions

This section reviews and presents a summary of the key variables affecting hydrogen's acceptability. It also provides some possible future research directions to pursue going forward. The literature on hydrogen acceptance has indicated a limited level of public awareness, a deficiency in adopting a human-centered approach, and a tendency to view end users in HET systems as obstacles to hydrogen deployment rather than valuable contributors to the design process [29]. The study of [31] investigated perception measurement in hydrogen refueling stations and discovered that perceived usefulness increases technology and infrastructure acceptance, whereas perceived risk has the opposite effect. Positive correlations were also observed between safety and public opinion of hydrogen-powered cars [72]. The cost, air pollution reduction, and health benefits of hydrogen were all found to impact its acceptance. Also, government trust in risk management and the industry's commitment to climate protection influence support for the hydrogen export industry. Effective communication, engagement, and financial policies were also found to be very critical to society's acceptance of hydrogen [108]. It has also been discovered that plain or straightforward messaging can affect people's perceptions of emerging technologies. Short and widely distributed communication formats are critical as mediatization trends develop. Brief messages should align with community values and appeal to a broad audience to be widely accepted, particularly in media-saturated societies. According to the study of [109], short messages work better with urban residents because there is a higher likelihood of hydrogen use in urban areas where hydrogen can be injected into distribution networks, and hydrogen cars are also more common. Furthermore, research indicates that risk perception levels impact public acceptance of hydrogen stations. Men were more likely than women to respond favorably to a survey, and it is possible to enhance risk communication in the construction of hydrogen stations by reducing fear and increasing acceptance by giving precise risk information [98].

The literature review findings suggest that before developing and implementing a large-scale hydrogen supply chain, project managers, planners, engineers, and policymakers should take a whole-systems approach and collaborate at the local, regional, and national levels. This will aid in developing incentives and ensuring commitment from key actors [110]. Very little information exists on studies focusing on various stakeholder groupings within the hydrogen value chain. Studies on perceptions ought to focus on various stakeholder groups to understand how society views the acceptance of hydrogen energy. The evaluation of research on social acceptance highlights how vital cultural narratives and patterns are in determining acceptance. Ethnographic studies can help researchers understand how cultural contexts affect how people perceive hydrogen energy, such as how some cultures prefer grassroots, community-driven solutions or trust government-led innovations. Particularly in distributed energy systems, a thorough understanding of acceptance should consider stakeholders' acceptance in addition to that of early adopters or the general public. It is important to consider elements like access equity, resource scarcity, and support for collective action. Discourse analysis emphasizes the need for multi-level and institutional perspectives and increased reflexivity and alignment between research findings and practical implications [34]. Qualitative interviews with policymakers, regulatory bodies, and legal experts can identify barriers to comprehensive hydrogen policies, including policy resistance, political will, and lobbying group influence. Furthermore, it appears most studies surveying one's willingness to accept hydrogen are concentrated mainly in China, the United States of America, and parts of Europe, leaving out countries in Africa and South America. However, Africa has been identified as a potential key player in the global hydrogen economy, with several countries on the continent poised to become large-scale producers of green hydrogen due to the huge RES potential [111]. It is, therefore important for futures studies to assess the continent's readiness to accept this new energy source. This will help stakeholders fashion appropriate policies and strategies for developing the sector on the continent. Future studies should examine consumer acceptance at various geographic scales and the social effects of hydrogen infrastructure on nearby communities. Large-scale quantitative surveys are thus essential for comprehending how the general public, across various demographics, views the safety, environmental impact, economic viability, and technological trust of hydrogen energy. Additionally, to better understand the acceptance of hydrogen energy, in-depth qualitative interviews or focus groups can reveal underlying misconceptions, fears, and knowledge gaps about the technology, especially emotional or psychological barriers like skepticism about new technology or fear of explosions.

Moreover, models such as the Diffusion of Innovation can be used by researchers to examine how new hydrogen technologies are adopted by different industries and users, spotting possible obstacles like high upfront costs, a lack of knowledge, or uncertainty. Finally, town hall meetings, citizen panels, and public consultations can be used to learn more about the needs, wants, and worries of local communities with regard to the adoption of hydrogen energy. To encourage involvement, this could entail interactive demonstrations or educational activities.

Conclusion

Research on hydrogen energy acceptance has recently received much attention from various researchers. As such, this study reviewed the literature examining the factors influencing the acceptance of hydrogen energy within the last two decades, using a blend of systematic, bibliometric, and content analysis methods. According to the study, hydrogen energy acceptance research has seen steady growth, with 350 authors involved and an international co-authorship rate of 12.96 %. The research is impactful, with 34.8 citations per document, indicating a multidisciplinary approach to tackle complex aspects of hydrogen energy adoption. The research's high citation rate may inform policy decisions and further studies. Japan, Germany, and China dominate hydrogen energy research, reflecting their national strategies for cleaner energy sources and reducing carbon emissions, while European countries contribute significantly. Global research on hydrogen energy adoption involves countries such as North America, Europe, Asia, and Australia. However, gaps exist in Africa and South America, as there is virtually no studies from those regions yet, affecting regional acceptance. International cooperation is crucial for overcoming challenges and accelerating innovation. The literature on hydrogen acceptance shows limited public awareness, a lack of a human-centred approach, and a tendency to view end users as obstacles. Perceived usefulness, safety, cost, air pollution reduction, and health benefits impact acceptance. Industry dedication to climate protection and government trust also influence support. Efficient financial policies, participation, and communication are all crucial for hydrogen acceptance, with short, widely distributed messages beneficial for urban residents and risk information reducing fear.

One limitation of the study that has to be highlighted is the fact that this study only considered papers written in the English language; however, it could be possible that some good studies in other languages could be missed. Secondly, although Scopus is the largest scientific database, other databases like the WoS may also have studies on the topic that may have been missed. However, despite these shortcomings, the study has been structured to give a complete understanding and representation of the current trends and evolutions on the subject matter. Appendix.

CRediT authorship contribution statement

Flavio Odoi-Yorke: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ephraim Bonah Agyekum:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Farhan Lafta Rashid:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Formal analysis. **John Eshun Davis:** Writing – review & editing, Visualization, Project administration, Investigation, Data curation. **Hussein Togun:** Writing – review & editing, Validation, Resources, Methodology, Formal analysis, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

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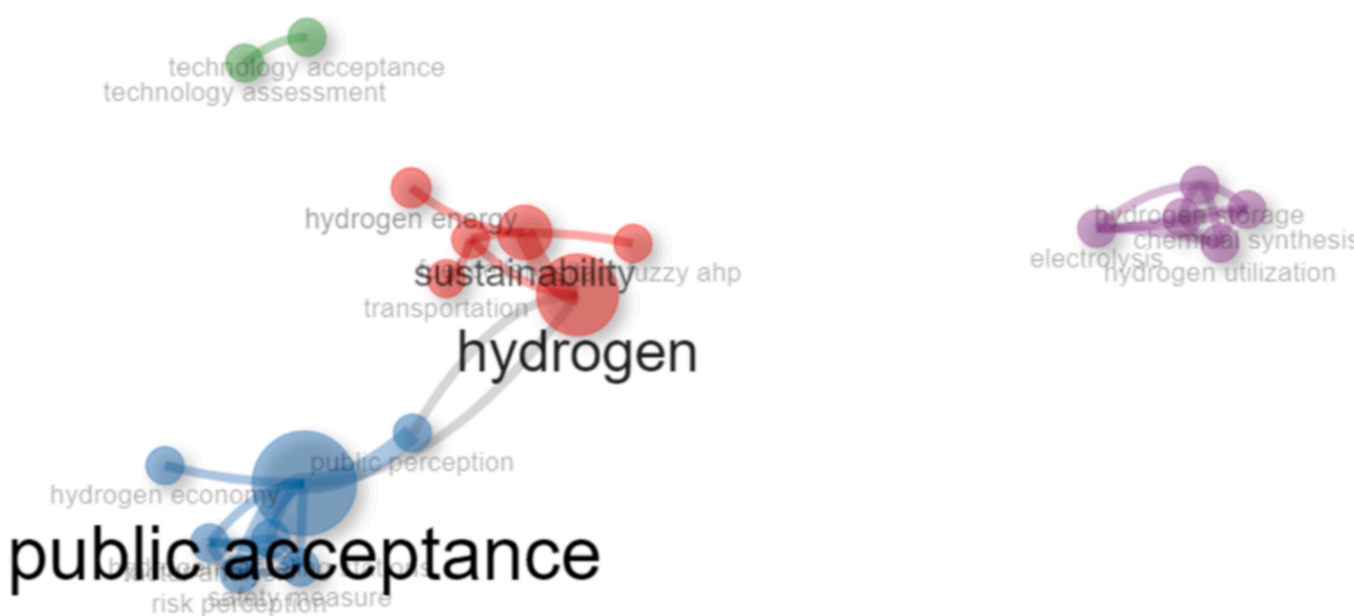

Fig. A1. Co-occurrence Network

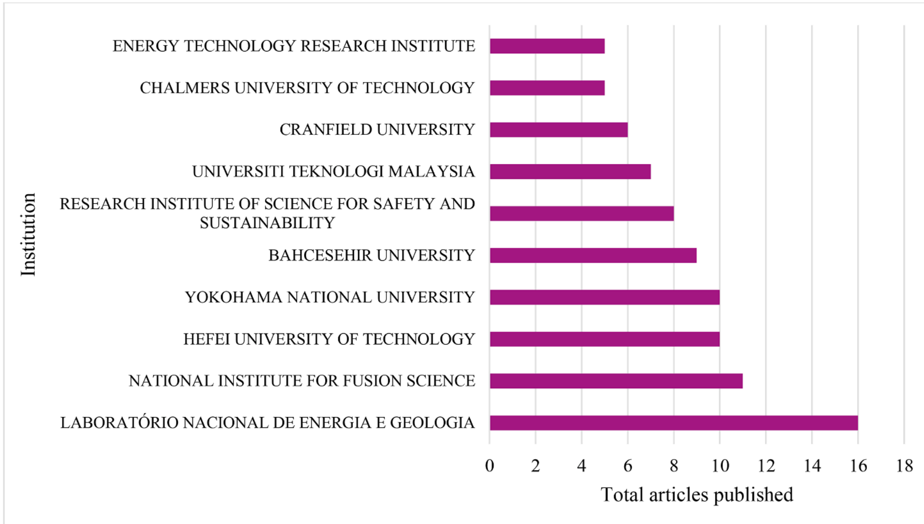

Fig. A2. Top 10 institutions with most publications

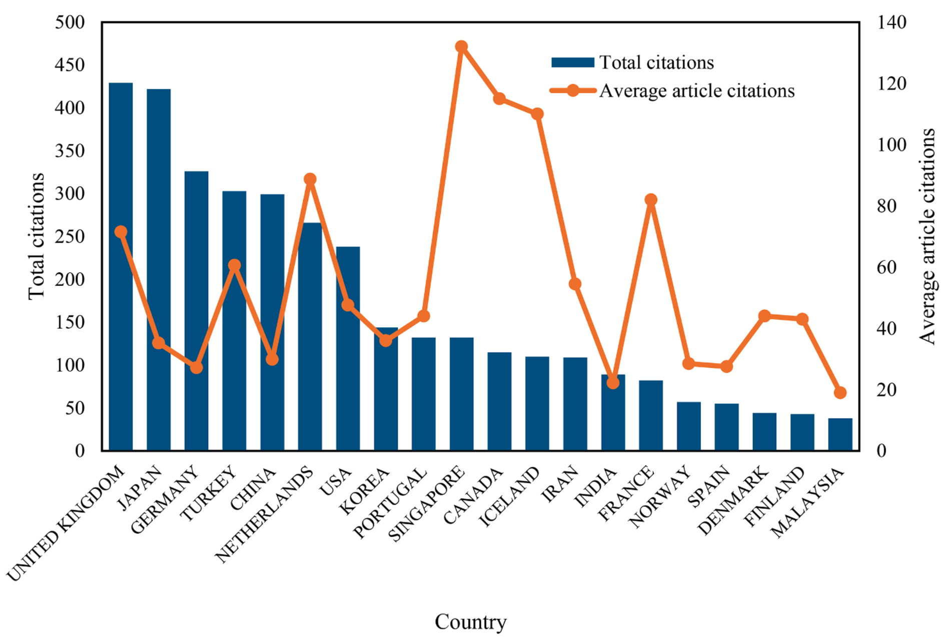

Fig. A3. Total citations per country

Data availability

Data will be made available on request.

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