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Review Article

Hydrogen electrolyser for sustainable energy production: A bibliometric analysis and future directions

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HIGHLIGHTS

- A comprehensive review on hydrogen electrolyser is analysed for future research directions.
- The problems, state-of-the-art technology, design, and performance evaluation is reviewed.
- The control strategies are significantly boost the efficiency of hydrogen electrolysers.
- A statistical analysis on electrolyser models, open issues, and future research trend is investigated.
- This review will contribute to improve the efficiency and sustainability of electrolyser technology.

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ABSTRACT

Sustainable energy demand drives innovation in energy production. Electrolysis of water can produce carbon-free hydrogen from renewable sources. This paper presents a bibliometric analysis of recent and highly referenced research on hydrogen electrolysers utilising the Scopus database to shed insight into future trends and applications. It has been discovered that the most frequently published type of study for top-ranked papers is the formulation of problems and simulations (38.3%), followed by a study of the state-of-the-art technology assessment (32.5%), laboratory research, design, and performance evaluation (24.2%), and reviews (5%). In general, 33.33% of articles focused on controlling hydrogen electrolyser efficiency. This study used different case studies from the global literature to conduct a complete evaluation of the electrolyser statistical analysis of the present state of the art, models or modes of operation, key challenges, outstanding issues, and future research. This evaluation will aid researchers in building a commercially successful hydrogen electrolyser.

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Contents

Introduction

The surge in global energy consumption over the last decades is due to both population growth and rising standards of living [12]. The world is currently confronted with a serious challenge due to climate change [34]. The International Energy Agency (IEA) predicts that worldwide energy demand could increase by approximately 9% by 2030. In 2050 and 2100, global power growth is expected to average around 30 and 46 TW, respectively [5]. At present, fossil fuels (oil, coal, and natural gas) are the predominant sources of energy used to meet global energy demands [6]. The diminishing energy reserves of these fuels render them unsustainable. According to BP Company, “Statistical Review of World Energy” (London, UK) [7], oil and gas reserves may be exhausted in 50 years. Also, the anticipated coal exploitation period is 132 years. This exploitation time was determined by considering 2019 confirmed reserves and the production that is happening right now. Although fossil fuels meet a large amount of global energy demand, they have a significant negative impact on the environment in a variety of ways that are undesirable to humanity, such as greenhouse gas (GHG) emissions, global warming, acid rain, poor air quality, and so on [1,8–10]. In addition, they are the main source of carbon dioxide (CO_2) emissions, which account for up to 82% of estimated GHG emissions [11]. The increasingly obvious repercussions of climate change have focused on recent global efforts to phase out fossil fuels [12]. Further, the world's unrelenting energy demand and finite fossil fuel supply, combined with concerns about sustainability and environmental impact, require the development of innovative carbon-free energy approaches [3].

Shifting the transition from fossil fuels to low-carbon sources of energy would be accomplished through technological advancements, particularly in the field of renewable energy [13]. Renewable energy (RE) resources can play an essential role in the transformation to a clean and environmentally friendly energy system [10,14]. Record renewable energy capacity increases can be ascribed to fast-lowering prices and profitability, especially for solar photovoltaics and wind power. In 2017, renewables provided 25% of global electricity. After three years of steady carbon dioxide emissions from 2014 to 2016, they dropped 1.4% in 2017 [14]. The variability and intermittency of RES constitute the most significant barrier to achieving 100% real RE [15–17]. In the future, it is anticipated that huge amounts of renewable electricity will also be supplied to larger power networks. For instance, Germany aims to generate 80% of its electricity from RES by 2050 [17]. In addition, Germany's Federal Government has opted to halt the production of nuclear energy by 2022, and where concrete objectives for the proportion of power produced from renewable sources have been established and required [18,19]. Using RES, Japan intends to lower GHG emissions by 39% for the residential market and 40% for the commercial industry by 2030 [20]. The Netherlands Government's Hydrogen Strategy explicitly highlights the requirement to import hydrogen produced by renewable electricity [19]. Similarly, the Chinese government is proactively transforming the electricity system by reducing the number of coal-fired power plants and boosting the proportions of natural gas and renewable energy [21].

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Therefore, technical adaptation is necessary (e.g., requiring a high level of energy availability and storage capacity for electrical industries and the transportation sector [22]), particularly in terms of regulating fluctuating energy supply and demand [10,18]. As global warming and environmental degradation increase, the importance of developing RES has expanded [3,8,23]. Renewable energy, which accounted for half of the world's energy consumption expansion in 2018, is anticipated to rise from 4% to 15% by 2040 [24]. Hydrogen has been looked at as a possible way to carry energy that could help spread renewable energy, replace fossil fuels, and cut down on pollution [3,8,12,25,26]. It is attainable when hydrogen is extracted from renewable water sources. Hydrogen also has the potential to be generated entirely from renewable sources in the long term [27]. This is attributed to the reason that electrolysis produces hydrogen with a high degree of purity (99.999%) [3], and is environmentally beneficial, as specified in the basic reaction as per the following equation [18].

$$1H_2O + Electricity\left(237.2kJ.mol^{-1}\right) + Heat\left(48.6\ kJ.mol^{-1}\right)H_2 + \frac{1}{2}O_2 \quad (1)$$

Hydrogen is the most common chemical element and is notable for being lightweight. It combines with oxygen in water and nitrogen, carbon and oxygen in living substances. Hydrogen is not the primary source of energy and must be acquired through a number of different processes [28]. When separated from other elements, it becomes an alluring energy carrier [2]. Hydrogen is a clean, sustainable energy source because it produces pure water and emits no CO_2. One more advantage of hydrogen is that it possesses a high energy density [8]. The energy density of hydrogen is 140 MJ/kg, which is greater than twice that of ordinary solid fuels (50 MJ/kg) [29]. The quantity of water on the planet enables hydrogen production to be relatively sustainable. Electrolysers have become the essential technology that generates hydrogen from water and electricity. Electrolysis is the use of electricity to convert water into oxygen and hydrogen. An electrolysis-based water split presents interesting synergy prospects with renewable energy. Hydrogen can also be created by utilising RES such as solar, wind, and nuclear power [15]. As a by-product of the intermittent nature of some RES, hydrogen can be created before use, making it appropriate for both dispersed and centralised production attached to isolated RES. Electrolyzer-produced hydrogen is suited for use in fuel cells that promote distributed energy backup, self-sufficient power plants, and cogeneration [8]. Notably, fuel cell and electrolyser technology can be utilized to resolve the intermittent nature of renewable energy, which may be a benefit for fuel cells as an increasing variety of countries shift to renewable energy to reduce greenhouse gas emissions [15]. Also, the benefits of hydrogen as an energy carrier include its high energy density and ability to be converted to electricity through water electrolysis. Additionally, hydrogen can be produced domestically, lessening a country's reliance on imported energy supplies [28].

Over the past few years, the integration of hydrogen into power networks has advanced gradually from production and storage to safety concerns and re-electrification. Hydrogen energy storage is an efficient approach to generate electricity utilising fuel cells [30]. Hydrogen can indeed be preserved as a pressurized gas, cryogenic liquid, or solid fuel like metal hydrides and carbon compounds [31]. This alternative has favourable hydrogen storage properties. Developing an economical solution to store hydrogen is essential to renewable energy concerns [31,32]. Numerous studies have been conducted to assess the current status of hydrogen network design using innovative methodologies, promising advancements, and future developments [33]. Extensive research initiatives are currently analysing and exploring the requirements, operation, impact, prospects, and constraints of transitioning and implementing hydrogen-based energy delivery toward the attainment of a civilization free of carbon [34], e.g. in Australia [35,36], Germany [37], Japan [19,20,38], China [24,39], France [40], Canada [41,42], India [43,44], UK [45], South Africa [46,47] and Turkey [48,49]. There is widespread agreement that hydrogen production using RES holds incredible potential for the sustainable growth of the globe to expedite the production of the green hydrogen production chain [50]. Hydrogen produced by water electrolysis (utilising renewable/clean electricity) is portable and marketable [12,51]. For clean hydrogen technologies to contend alongside fossil fuels and dominate the market, solutions should attain a competitive level [41].

Bibliometrics is a vital topic of study since it provides specific and historical findings that may be utilized to forecast future research trends. It is a multidisciplinary field that employs mathematical and statistical approaches to conduct quantitative analyses of all areas of knowledge [52]. Statistical techniques can aid in the mapping and development of several criteria for records management. The initial development of bibliometrics back to the early 20th century. Allen Richard, a renowned British researcher, came up with the term “bibliometric” in 1969 in place of “statistical bibliography.” This term's emergence heralds the formal beginning of bibliometric [52]. At present, this kind of research is receiving increasing attention. The essential advantage of bibliometrics is that it allows scholars to do in-depth analyses of certain study topics, such as measuring citations, geographic location, authors, university administrators, and countries, and drawing incredibly valuable findings. On the other hand, analysing the most cited publications may be useful in identifying “remarkable” positions in the study field and highlighting areas for further research. The study employs bibliometric methodologies and provides innovative empirical insights into academic publishing and impact quality. Its analyses high-quality journals that publish the output [53]. Bibliometric has been extensively employed in the past for hotspot research [54], subjects [55], co-authorship analysis [52], co-citation analysis, countries that publish global research output, and the growth of entire subject fields.

Numerous bibliographic indicators have been conducted to analyse bibliographic data, including the cumulative amount of literature and citations [56,57], the h-index [58], citations per paper [59], and citation thresholds [60], and several other related indicators. This study analysed hydrogen electrolyser articles from 2012 to 2022 by selecting the top-cited articles based on the number of citations per paper. This is because citation is generally considered the most suitable way of determining the impact factor of authors, articles, and journals [59]. The large network of academic citations contains the accumulated wisdom of hundreds of thousands of authors, demonstrating what is popular, fascinating, and relevant to the field of the project. Generally, authors prefer to publish in journals with greater citation potential; this fact correlates with the evidence that the world's best universities have the most highly cited papers. The citations per faculty score reflect this performance, indirectly establishing the university's global reputation [58]. Furthermore, this profession receives scholarly peer review credit and encourages global study and academic collaboration. Researchers can use citation data to decide which journals to send manuscripts to, librarians can use it to decide which journals to subscribe to, funding agencies can use it to evaluate grant proposals, and tenure committees in determining tenure cases [61].

More specifically, the paper uses bibliometric analysis to develop the development path of the citation network and the theme evaluation of this field. Scopus was used to compile a set of the most referenced articles on the subject of hydrogen electrolysers. In the hydrogen electrolyser field, which is considered a hot topic for sustainable energy, no bibliometric analysis study for the published papers with respect to hydrogen electrolyser research has been done yet. With limited academic analysis and extremely scarce resources as beginning points, this article can assist researchers in hydrogen electrolysers in developing new information and building on current scientific traditions while also charting new research paths. Hydrogen has become a critical medium in energy transitions due to its ability to be generated from RES, re-electrified, can provide heat and electricity, and be stored for future use. This research is analysed in line with the literature reviews from 2012 to 2022. This study will contribute to the characterization of the issues' evolutionary trajectory and the advancement of the research. Thus, the main objectives of this research are summarized as follows:

- Provide the researchers with a better understanding of the history, evolution, current updates, and recent trends in the field of hydrogen electrolyser.
- Deliver comprehensive analysis of the top-most cited studies on hydrogen electrolyser for sustainable and efficient energy production.
- Based on the analysis and review of recent research gaps, concerns, and challenges, this study provides future prospects and recommendations for deploying and improving hydrogen electrolyser toward a sustainable and green energy transition.

The paper has been organised in the following way: the second section summarises the review process and bibliometric method used to analyse the most frequently cited publications, which includes the criteria for inclusion and exclusion, selection process, research trends, and research outcomes extracted from the Scopus database. The third section presents the state-of-the-art of hydrogen electrolysers with the various aspects of hydrogen production, electrolyser, and hydrogen storage. The fourth section presents deeply analytical discussions that include research trends in scientific and country production, citation structure analysis in the last ten years, classification of study types and subject areas of research, distribution by the publisher, journals, categories (topics), and keywords. The fifth section presents the hydrogen electrolyser issues, challenges, and recommendations. In section six, the most-cited articles are used to show the final thoughts, work to be done in the future, and limitations.

Review process for the quantitative approach

The study is conducted to comprehensively review recent research findings on hydrogen electrolysers for sustainable energy production over the last ten years. Based on the Scopus database, this study uses bibliometric approaches to analyse papers published between 2012 and 2022. The third week of February 2022 was recorded as the date of the search because the number of articles may have changed over time as additional articles were published. Scopus is the world's largest database of interdisciplinary peer-reviewed papers, and it is continuously updated and expanded [62]. It provides a summary of global research output in the disciplines of engineering, science, social sciences, technology, the arts, medicine, and humanities, as well as other fields [63], which is why it is the optimal option for bibliometric review. This study's methodology was determined by evaluating the most-cited publications in the Scopus database, as indicated in Fig. 1. The evaluation of surveying methodologies in the Scopus database was undertaken in three steps as follows:

Surveying selection process

During the primary research on the field of hydrogen electrolyzer, a total number of 1242 papers in the first screening was found from 1970 to 2022 in the Scopus database. The three significant keywords "hydrogen electrolyser", "control", and "sustainable energy" were the most applicable to the subject matter of this bibliometric analysis study. In the second screening stage, 360 papers were identified using two filtered keywords: control and sustainable energy and limitation for the years 2012–2022. Next, 360 articles were selected based on the field of Engineering and Energy, and then 328 papers were extracted based on the document article's type and the language of English. Finally, around 184 articles with the highest citations were selected based on their titles, abstracts, focus, citations, content relevancy, and practical contribution.

Inclusion, exclusion, extraction, and analysis

While filtering the most cited articles in the hydrogen electrolyser in grid application, the inclusion and exclusion criteria were established to examine current studies and valuable study materials from Scopus. The following criteria for inclusion and exclusion are provided, which are: (*a*) the papers were extracted based on the hydrogen electrolyser field of research with the keywords "control" and "sustainable energy" used; (*b*) papers were chosen from a limited duration of years between 2012 and 2022; (*c*) subjects of "energy" and "engineering" are only considered for scientific fields; and (*d*) the publications in the form of articles written in English were

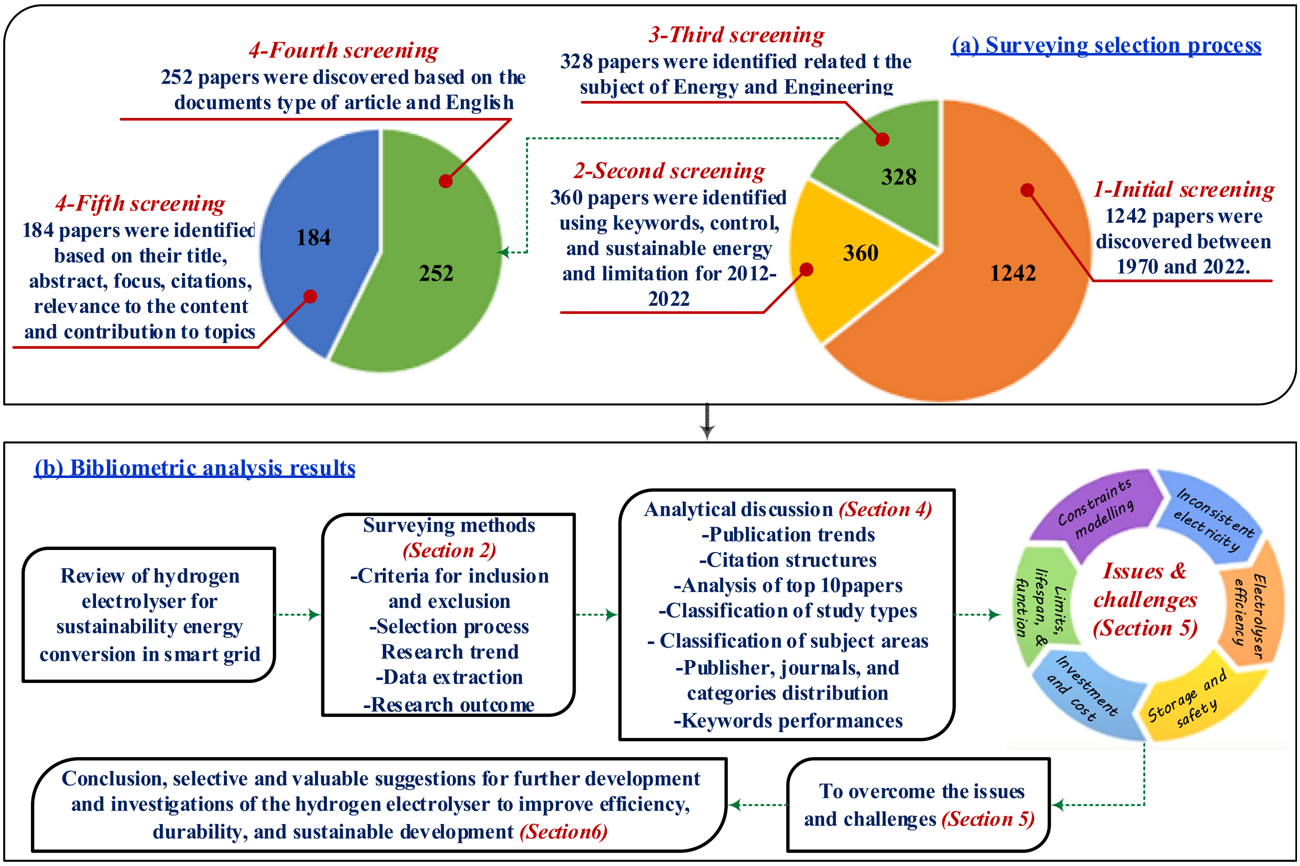

Fig. 1 — Flowchart and visual representation of surveying methods utilising the Scopus database.

selected. Based on the inclusion and exclusion criteria, the contextualization, analysis, comparison, and reviews of the top most-cited articles were achieved with the following sequence: (*a*) the survey's methodology includes inclusion/exclusion, survey selections, trends, data retrieval, and study characteristics/findings; (*b*) a review study on the state-of-art that include had been published encompassing aspects of hydrogen production, electrolyser, and hydrogen storage has been published; (*c*) analyses discussions concentrated on citation patterns and publication trends, citation structures, the top 10 papers analysis, classification of study types, classification of subject areas, publisher, journals and categories distribution, and keywords performances. The analysis involved relating, comparing, and elucidating; and (*d*) the main issues or challenges include inconsistent and fluctuating electricity; modelling constraints; electrolyser working limit, life span, function; electrolyser efficiency; storage and safety concerns; high investment and operating costs were described. The solutions underlying challenges in hydrogen electrolyser were revealed.

The following variables were used to retrieve data on papers from the Scopus database: (*a*) list of the most frequently cited articles; (*b*) name of authors as well as paper's publication year; (c) keywords; (*d*) amount of paper citations; (*e*) journal methods and systems; (*f*) study's field; (*g*) publisher of the top most frequently cited articles; (*h*) most prestigious journal and its impact factor (IF); and (*i*) country and (*j*) paper limitations or research gaps. Study limitations were included to provide future insights and contributions to the developing hydrogen electrolyser research sector. Finally, an analysis of the most highly cited publications was conducted to provide a clear overview of the hydrogen electrolyser for sustainable energy in grid applications. According to the review results, the final analysis reveals survey findings and makes future research recommendations based on relevant output from other articles.

Research trend and review analysis

Fig. 2 illustrates the annual trends in publications relating to hydrogen electrolysers from 1970 to 2022. Between 1970 and 2022, 1242 papers were published on hydrogen electrolysers with a total number of citations of 31,005. There were 374 publications between 1970 and 2011; however, between 2012 and 2022, there were 868 publications. The cumulative citations from 1970 to 2011 were 11,696, whereas from 2012 to 2022, there were 19,309 citations. By comparison, it can be shown that research on hydrogen electrolysers has grown rapidly in the last ten years, increasing by 70% over the period 1970 to 2011. The overall number of citations in the last ten years is also more than the entire number of articles from 1970 to 2011, at 62.3%, despite just being ten years. It shows that hydrogen electrolyser development is gaining traction and is widespread.

In 1970, the first paper on hydrogen electrolysers was published [64]. Shesadri et al. [64] examined the functionality of a

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modified electrolyser for producing hydrogen. The results were a decrease in carbonate content in the electrolyte and an increase in hydrogen generation. Refer to Fig. 2; since 1970, research publications have increased significantly in the following years until 2011. Between 2012 and 2014, an increasing number of scholars began to study in this field, resulting in 97 articles (11.17%). After 2015, the trend began to decline, and the amount of literature tends to grow again, with the highest collection of documents reaching 141 (16.24%) in 2021. For citations reported, it's remarkable that more than a thousand citations were documented from 2007 to 2020. The highest citation count was 3466 in 2017, followed by 3402 citations in 2012 and 2653 citations in 2016. Citations reached 467 and 10 in the years 2021 and 2022, respectively. Generally, papers published in the previous year garnered more citations than those published recently. This year of publishing will likely have a greater citation count than in previous years due to history receiving more citations Also, we focused our analysis on papers published between 2012 and 2022 for other reasons, such as their high number of citations and their recent progress.

Numerous factors contribute to rapid growth. Firstly, as green energy advances, people realise that hydrogen is a potential energy carrier to decarbonize industries, including electricity production, manufacturing, and transportation. Also, governments and scientists consider hydrogen as a possible alternative to fossil fuels [25]. Second, this research has drawn attention to reducing GHG emissions using RES (wind, hydro, solar) and nuclear energy [7]. Third, using hydrogen as a fuel may help alleviate various environmental and societal issues such as global warming, polluted air, and consequently climate change [65,66]. Based on the review analysis, it can predict that the number of publications will increase in 2022 and the coming years. This is due to certain governments prioritising RE in their plans [67]; thus, this hydrogen electrolyser research may result in a tremendous increase in 2022 and the future. Following this stage, a more extensive study of the research trend from 2012 to 2022 will be discussed in a later section.

Among the highly cited papers, Refs. [68–70] earned more than 83 citations. Samsatli et al. UK had the article with the highest citations (114) in 2016. It was published in the International Journal of Hydrogen Energy. Bareiβ et al. [69] from Germany earned the second-highest citation with 89. This article was published in Applied Energy in 2019, with an IF of 8.426. With 83 citations, Maroufmashat et al. [70] from Iran obtained the third-most citations. This article was published in the International Journal of Hydrogen Energy and included six authors. It is worth mentioning that the publisher of the top three articles is Elsevier. Each publication from the hydrogen electrolyser has a great deal of information, including the publication year, authors, address of the authors, title, abstract, source journal, subject categories, and references, all of which serve as the fundamental parameters for bibliometric analysis. According to the review analysis used in this study, such as output analysis, co-occurrence analysis, and network visualization have been highlighted. The articles have also examined a range of databases, approaches, objectives, concepts, and contributions to hydrogen electrolyzer research. It can be utilized to develop fresh ideas for future investigations due to their data presentation and analysis. The results of the aforementioned analyses can be classified as follows: the number of citations, methods and systems, limitations or research gaps, study types, subject areas, keywords, topic, publication year, publisher, document type, source type, and country production. Lastly, we provide the results of the bibliometric analysis.

State-of-art of hydrogen electrolyser

Despite the dangers of climate change and global warming, our world's energy and transportation systems have evolved

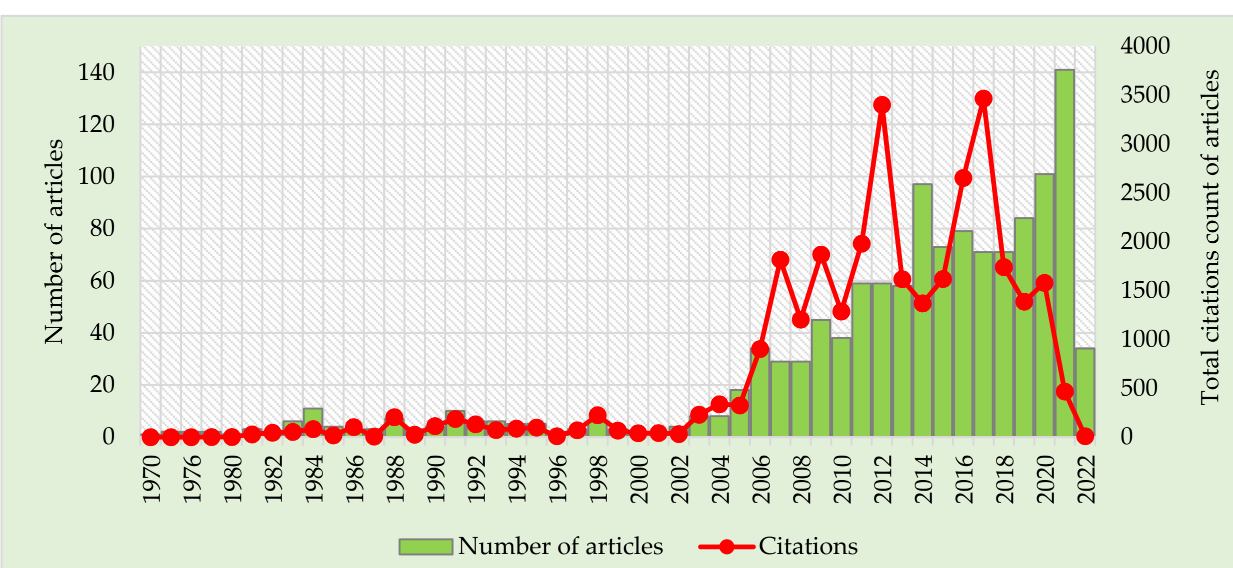

Fig. 2 – Annual trends in publications relating to hydrogen electrolysers.

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dramatically, with growth in RE sources, energy-saving measures, and electric vehicles (EV). That seems to be that the world is already moving toward cleaner energy. Hydrogen is a clean, sustainable energy carrier that emits no carbon dioxide (CO_2) [3]. Hydrogen is widely considered a potential cost-efficient clean energy source for the future economy [71]. It is the most prevalent element in the universe and has been found in water and organic substances on earth [10,14,71]. It is the lightest, simplest element with one electron and one proton [14], a colourless, tasteless, combustible gas [10]. It also has a high energy density per unit mass in comparison to conventional fuels; 1 kg of hydrogen contains around 120 MJ (= 33.33 kWh), which is more than double the energy density of most conventional fuels [72]. It is a non-toxic, environmentally friendly, and advantageous energy carrier with water as hydrogen can be produced from non-renewable and renewable sources [71]. Hydrogen can be produced from renewable sources such as wind, solar, hydro, wave, geothermal, and biomass [71].

The production process affects the hydrogen gas quality [73]. Identifying contamination levels helps in developing rules and expectations for hydrogen purity for gas grid injection. Technology in H_2 production from RE is essential to addressing energy and environmental concerns in a clean, efficient, effective, reliable, and cheap approach [38]. Numerous ways are available to produce hydrogen from renewable sources. Water electrolysis is the most widely accepted approach, which uses direct current (DC) electricity to dissolve water into O_2 and H_2. Solid oxide electrolyser (SOE), alkaline electrolyser (AEL), and proton exchange membrane (PEM) are prominent water electrolysis technologies [39].

Alkaline electrolysis machines on a large scale are an established industrial process capable of producing 200 Nm^3 of hydrogen per hour [32]. It is a reliable and safe electrolyser [74]. These AELs electrolytes are aqueous sodium or potassium hydroxide (NaOH, KOH). Oxygen and hydrogen are created at the anode and cathode electrodes, respectively [10]. The electrolyser's operating temperature is restricted to 80 °C due to the limitation in asbestos usage [32]. Moreover, AEL with operating temperatures of up to 150 °C is being developed. These electrolysers are excellent for hydrogen production on a big scale. The purity of hydrogen and oxygen can approach 99.9 vol% and 99.7 vol%, respectively [74]. Owing to hydrogen's lower heating value, AEL typically achieves 62–82% voltage efficiency [74,75]. PEM electrolysers are using a solid polymer membrane electrolyte instead of a corrosive liquid. Typically, the electrodes are composed of noble metals, such as platinum or iridium [74]. PEM electrolysers are presently expensive to manufacture. At the anode, water is oxidised to produce oxygen, electrons, and protons, while protons are converted at the cathode to form hydrogen [32]. For the electrolysis process, deionized (DI) water of the highest purity is necessary [76]. PEM electrolysers are available commercially for applications utilising small-scale production [74]. The hydrogen purity exceeds 99.99 vol% (in certain cases, it reaches 99.999 vol%) [77]. Their efficiencies range between 50 and 80% [32]. SOE steams at high temperatures (up to 1000 °C), resulting in higher efficiency than AEL or PEM electrolysers [74]. SOE is currently in the research and development phase and is employed on a laboratory scale, producing up to 5.7 Nm^3/hr and 18 kW. Oxygen is formed at the anode when oxide anions flow through the solid electrolyte [74].

Hydrogen has high gravimetric energy density but low volumetric energy density, preventing its usage in fuel cell vehicles [32,72]. The storing of hydrogen energy is an emphasising for fuel cell electricity production. The hydrogen storage system should complement vehicle size without additional weight and provide an adequate driving range. Hydrogen storage is a crucial part of the hydrogen economy, and developing safe, dependable, affordable, and effective storage techniques is really a challenge [32]. There are three methods for storing hydrogen: compressed gas (physical storage), cryogenic liquid hydrogen (physical storage), and solid-state storage. Most hydrogen is stored as compressed gas or liquid. Solid-state storage is still in development and depends on sophisticated materials [32]. Compressed hydrogen tanks are most frequent in fuel cell vehicles (FCV). Since 2010, over 80% of the world's 215 hydrogen refueling stations have utilized this high-pressure gaseous storage technology [31]. For instance, prototype vehicles: Toyota FCV, Honda CFV, Mercedes Benz, etc are currently undergoing tests used for the manufacturers [72]. However, liquid hydrogen storage is infrequent for many reasons. Hydrogen boil-off is a challenge. Even in well-insulated tanks, liquid hydrogen storage can evaporate, causing hydrogen loss [78].

For large-scale applications, researchers must develop economical and practical hydrogen storage and manufacturing, particularly for producing energy in fuel cells, the most advantageous technique to acquire energy from hydrogen [30]. RES-powered hydrogen production-storage units have been modelled. Khalilnejad et al. [79] presented a hybrid wind–PV model for electrolytic hydrogen production. The imperial competitive colony algorithm optimizes this system's operation. Olivier et al. [80] used simulation to combine RE with hydrogen production and storage. Han et al. (2015) [81] examined electrolysis using pressure, current density, temperature, membranes thickness, and electrode (PEM electrolyser Ohmic loss model). Zhang et al. (2017) [82] evaluated the grid-connected PV-H_2/battery storage system. Hydrogen and battery storage are compared. One situation promoted batteries, while the other promoted hydrogen. Gonzatti and Farret [83] simulated an AEL, metal hydride storage, and a PEM FC system. Direct measurements confirmed the findings' accuracy. Kavadias & Kaldellis [79] optimise and size a HydESS employing an AEL. This method computes a hydrogen-based system's rated power for maximal storage and production.

Review papers on hydrogen production, electrolyser, and hydrogen storage have been published that include references [8,23,77,84–92]. The literature was studied from the years 2012–2022. This study concentrated on literature published between 2017 and 2022 in references [8,23,84–86,91,92]. Nikolaidis & Poullikkas [86] analysed the principal hydrogen production technologies and their technical properties. Maggio et al. [23] evaluated recent literature on hydrogen production and deployment, focusing on the Power-to-Hydrogen concept, and conducting a comparative analysis to highlight the key economic, social, and environmental elements that should govern the future market. Thema et al. [91] investigated European power-to-gas (P2G) plants that produced hydrogen or a sustainable substitute for natural gas. Hirscher et al. [92] reviewed the various hydrogen production methods, their current state, and future possibilities. Egeland-Eriksen et al. [84] analyse lab-scale to full-scale, continuously operating hydrogen energy storage systems, in which 15 initiatives' concepts and performance are analysed. Yue et al. [8] analyse present and future developments in hydrogen generation, re-electrification, and storage technologies. Asghari et al. [85] reviewed metal-free seawater electrolytic catalysts, highlighting developments and difficulties.

Analytical discussions

Bibliometric techniques, or "analysis," are scientific specialities and a significant aspect of appraising research, especially in the scientific and applied sectors [55]. This bibliometric study using Scopus was performed in the third week of February 2022. All documents were discovered in the primary search, with the majority being articles (n = 1242). The total number of publications was calculated starting in 1970. After a final evaluation based on high-ranking citations in hydrogen electrolyser for sustainable energy production and screening, documentation was reduced to 184 publications. Further analysis was conducted on these high-ranking citation papers. All papers were based on journal articles, and 100% were published in English. The data from top-cited hydrogen electrolyser articles were analysed using a variety of criteria, including the article trend in scientific production and their country's production, citation structure analysis, assessment of the top 10 most-cited articles in the hydrogen electrolyser field, classification of study types of research, classification of subject areas of researches, distribution of publishers, journals, topics; and assessment of the most frequently used keywords.

Article trend in scientific and country production

The annual analysis of published papers on hydrogen electrolysers is depicted in Fig. 3 (A). The pattern can be seen in the paper fluctuation graph over the period. However, annual publishing numbers increased gradually over the first five years of analysis, from 2012 to 2017, with a total number of

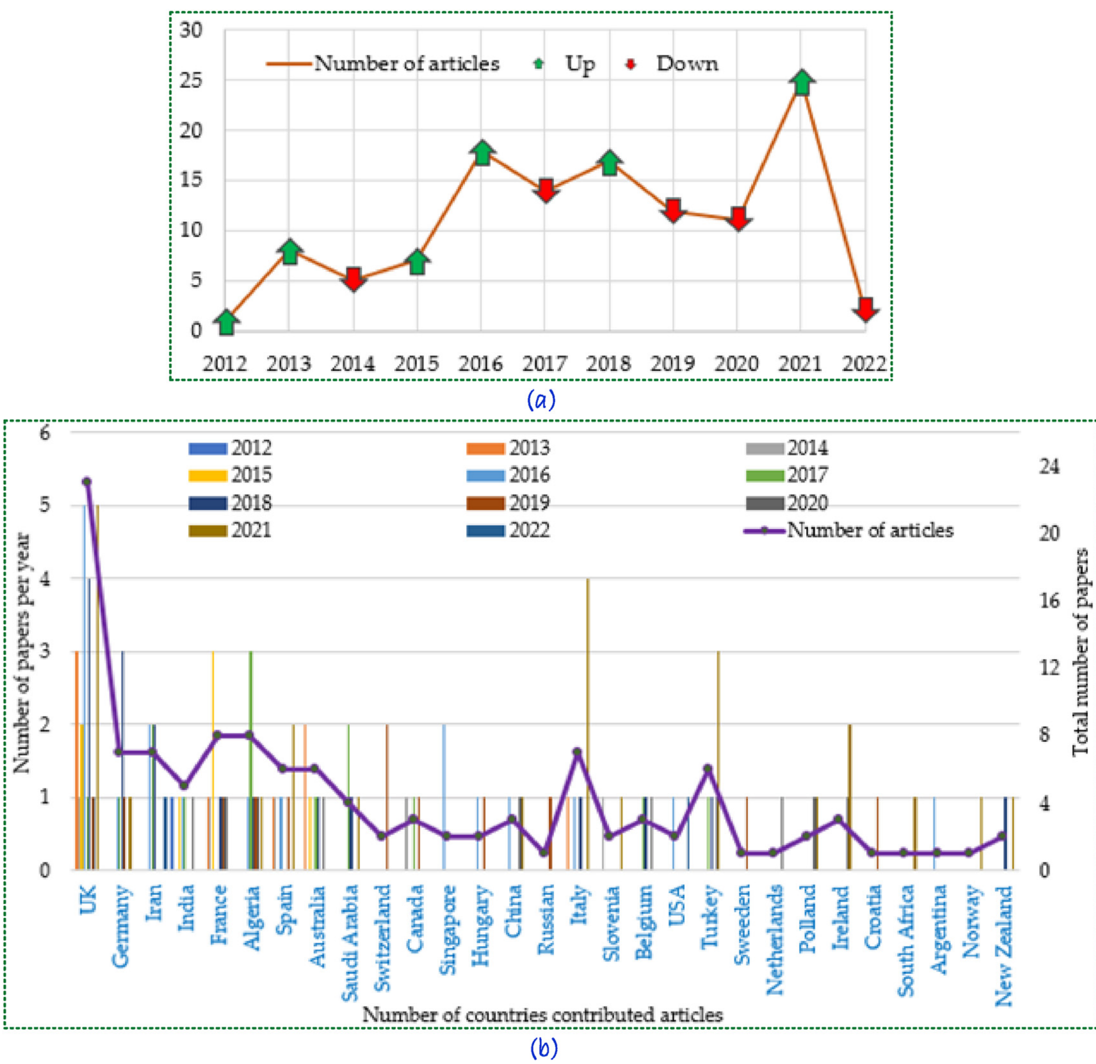

Fig. 3 – Distribution of the top cited articles according to (a) Number of publications of hydrogen electrolyser research per year and (b) Number of countries that contributed articles per year.

papers of 53. The years 2018–2022 exhibited rapid growth, but annual production for 2022 contributed two papers. In 2022, fewer publications were published due to the discovery of a Scopus article in the third week of February. In general, the increase in annual publications since 2012 could be attributed to an increase in worldwide energy research. Additionally, it is important to note that publication has increased steadily in the years leading up to 2021. Also, 2021 was the most productive year, with a total of 25 publications. However, it is premature to forecast for the year 2022 because this study is focused on determining the number of papers published in February 2022. However, this forecast indicates that publishing may see significant growth in 2022, based on the increasing tendency since 1970 (as illustrated in Fig. 2), which is necessary for industry-efficient strategies. This demonstrates that the hydrogen electrolyser field for sustainable energy is a promising study area.

As seen in Figs. 2 and 3 (a), a rapid expansion of a published publication demonstrates that hydrogen electrolyser research is generally recognised. This is because hydrogen can potentially reduce carbon emissions in the transport industry, which still uses almost all oil [68–70]. Hydrogen is often used in transportation, and grid electricity technologies are extremely appealing worldwide. Hydrogen is preferred because it is carbon-free nuclear energy, inexpensively generated from RE sources, and it swiftly recharges automobiles [10]. Also, hydrogen can be used as a transportation fuel, mitigating pollutant problems like urban pollutants and greenhouse gas emissions [70]. The technology for the various conversion processes all along the hydrogen value chain (electrolysis, storage, hydrogen-to-X synthesis, FC, and transportation) is nearing commercial maturity. PV and wind energy will be the backbone of 100% RES, as both are highly scalable and facilitated by hydrogen storage [56]. The insert word rank1 to rank10 in Fig. 3 specifies publication's ranking based on the first to ten highest-ranked articles for hydrogen electrolyser research.

As illustrated in Figs. 3 (b), 29 countries provide high-cited papers with high top citation counts. Each country contributed a different amount of paper between 2012 and 2022. In terms of countries, the UK, Algeria, France, Iran, Germany, and Italy are the top three most productive countries in terms of publications on bibliometric studies. The UK is the leader in creating scientific articles based on hydrogen electrolysers, with 23 publications. Algeria and France are the second most productive countries. The third most productive countries are Iran, Germany, and Italy. Scottish Power plans planning to build the world's largest electrolyser at a green hydrogen station in the UK. It would be near Glasgow, Scotland [57]. Many Algerian locations have a high solar radiation potential for hydrogen production [58]. Due to their proximity to the sun, southern Algerian regions have H_2 potential. Geographical expansion and the growth of international energy research tend to enhance study volume. RE, including hydro, reached 16.7% of French electricity in 2017. Wind, PV, and renewable biofuels contributed 7.5% of total electricity. In the coming years, the French electric system is likely to undergo many changes, particularly with renewables projects contributing 32% of total energy consumption by 2030 [59]. Germany boosted RE energy from 3% in 1990 to 32% in 2016 [35]. According to Germany's National Hydrogen Strategy, Germany will require 2.7 to 3.3 Mt of hydrogen (produced utilizing renewable power) yearly by 2030, and yet only 420 kt can be produced domestically [19]. By 2050, the government intends to meet 80% of its electricity consumption by utilising wind and solar energy [35].

Citation structure analysis of highly cited articles

Hydrogen electrolyser papers are studied, and top-cited papers from 2012 to 2022 were analysed. A high citation counts factor is essential as this research determines the characteristics that influence citations in publications that are actually interested and truly understanding what would be significant now [60]. Exploring high-citation publications listed by Scopus can be beneficial in this work as a study strategy that aims to identify and consolidate all available data on a specific topic to provide recommendations concerning hydrogen electrolyser investigations. Citation analysis is a well-known way to figure out how influential an author or article is on a topic [23].

The most cited article in the last ten years' analysis was by Samsatli et al. [68], with 114 citations. Mixed integer linear programming (MILP) has been used as a method and system for reducing UK network costs. The model determines the appropriate amount, position, size, energy transmission mode (electricity or hydrogen), transmission network topology, and hourly performance from each innovation. For literature gaps, results are limited by the database's technologies and may change if more technologies are introduced. Sensitivity analysis is required for the model. Bareiβ et al. [69] contributed the second most cited article, with 89 citations. The research recommends PEM water electrolysis (PEMWE) to reduce hydrogen market greenhouse gas emissions. PEMWE can minimize CO_2 emissions by up to 75% if the electrolysis system is only utilized for RE sources. Energy generation technology should be focused on overcoming the research gap. Maroufmashat et al. [70] published a third highly-cited article in 2016 with 83 citations. This research uses General Algebraic Modelling Software (GAMS) to stimulate and optimise power generating and storage systems. ES and power exchange constraints limit this paper's research. These top three papers were published by Elsevier in the Int. J. Hydrog. Energy (Samsatli et al. [68], Maroufmashat et al. [70]) and Applied Energy (Bareiß et al. [69]). The Int. J. Hydrog. Energy and Appl. Energy's most recent IFs are 5.816 and 8.426, respectively.

In summary, the majority of top-cited publications covered methods for hydrogen production. Hydrogen can be generated from fossil fuels or RE sources [69]. This is because hydrogen is not a self-contained energy source [94]. Although there are various methods for producing hydrogen from RESs, water electrolysis is the best approach accessible, as discussed in these top articles. The sustainability of hydrogen and RES is noteworthy. Hydrogen produced by electrolysis using PV or other renewable sources, e.g., wind or hydrogen power, emits no greenhouse gases. Furthermore, hydrogen is easier to store than electricity, especially for sustained periods to compensate for solar irradiation variability [95]. Hydrogen generation using RE sources can indeed be stand-alone or grid-connected. There is a hydrogen storage system that connects wind and PV systems to electrolysers to generate hydrogen [96–98]. Due to the unpredictability of renewable resources, the electrolyser working conditions are highly variable. It is possible to connect PV systems and WT to electrolysers using dc-dc conversion stages, which condition the electrical supply for the electrolysers while maximizing the power available from renewable sources. The stand-alone configuration uses electrolysers, FCs, and hydrogen gas collectors in isolated places without connection to the power grid. When the renewable systems cannot satisfy the load requirement, surplus electricity would be used to generate hydrogen for fuel cells. Surplus hydrogen can be utilized to heat homes, power FC automobiles, etc. [94].

However, the drawback of RESs is that they give us interrupted energies, most of which are constantly unavailable [68]. As a result, storage technologies are likely to become involved; their size, type, and region must be specified. A conversion process including FCs and electrolysers may also be required to convert electricity and hydrogen. The systems can be extremely complicated and incorporate a large number of alternate possibilities. Several methods and systems for hydrogen networks have been reviewed. Numerous models have been developed in recent years to optimise integrated energy networks that include inconsistent RES on the grid or without the grid. In general, the top-cited papers cover methods and systems including mixed integer linear programming (MILP) model [68,99,100], general algebraic modelling software (GAMS) [70,101], proportional-integral (PI) [102,103], genetic algorithm (GA) [104,105], hybrid optimisation of multiple energy resources (HOMER) [106–108], fuzzy logic controller (FLC) [101,109,110], particle swarm optimisation (PSO) [95,111] and model predictive control (MPC) [112–114].

The authors in Ref. [68] presented a MILP approach to optimise the design and operation of wind-hydrogen electric networks. Utilising MILP to reduce total network expenses in Great Britain. The approach was proposed to solve the problem of meeting all domestic transportation demands in the UK. Mukherjee et al. [99] used a multi-period MILP model to figure out the best way to optimise RE source sizing and operation, hydrogen storage and production (electrolysers), and an FC system in the region of Cornwall, Ontario. The research measures the CO_2 emissions savings that can be achieved by applying RE sources to fulfil Ontario's provincial grid's energy demand, promoting hydrogen-enriched natural gas for gasoline vehicles, and distributing hydrogen-enriched natural gas to natural gas end-users through the power to the gas concept. Gillessen et al. [100] employed a MILP approach to determine the optimal overall system cost for a dual electrolyser/battery system that is connected to a huge PV without a power grid. Recently, researchers are using artificial learning to create battery models from information rather than hand-engineering them in labs [115,116]. Because of the increasing use of renewable energy, utilizing battery energy storage has advanced rapidly in recent decades [117]. The outcome demonstrated that batteries can sustain electrolyser operation. However, the expenses of producing hydrogen are higher than installing additional electrolyser capacity or reducing electricity usage.

A multi-period mixed-integer dynamic optimisation model in the GAMS has been constructed by Maroufmashat et al. [70] to minimize the network's entire operational costs and the hydrogen's capital cost refueling station. Rouholamini et al. [56] constructed an offline optimiser by integrating MATLAB and GAMS. The results were utilized to construct a Sugeno-type fuzzy inference system for real-time EMAN. The generic mathematical model optimizes future hydrogen-powered community EMAN. Francis & Chidambaram [102] and Samani et al. [103] constructed a proportional-integral (PI) controller that responds to frequency deviation and provides the controller with a reference signal. As revealed in Ref. [102], the PI + controller provides improved transient and steady-state performance for interconnected power systems with hydrogen-generative Aqua Electrolyser. The simulation findings from Samani et al. [86] reveal that the PEM electrolyser's rapid dynamics allow for considerable flexibility, allowing participation in the auxiliary market. Optimisation techniques using a genetic algorithm (GA) have been applied by Burhan et al. [104] and Khalilnejad et al. [105] for the PV electrolyser system. The GA optimisation aims to maximise hydrogen production and minimize excess power, energy transfer losses, and overall yearly system costs. The HOMER numerical simulation software was utilized to optimise the RES-hydrogen energy system structure [106,108]. The HOMER software is utilized in Ref. [107] to evaluate the optimal network architecture and annual electricity profiles for the FC stack and electrolyser in a remote Australian household research study. Tabanjat et al. [109] demonstrated a 59 kW PEM electrolyser fuelled using a PV generator through a buck converter for H_2 generation.

FLC technique was utilized to regulate the water heating inside the hybrid PV-Proton Exchange Membrane Electrolyser (PV-PEM ELS). FLC was employed to increase the efficiency of the hybrid PV-PEM ELS system. Zhang et al. [110] integrate solar-powered hydrogen production systems with FLC-based power management to provide continuous off-grid electrical energy independence. Rouholamini et al. [101] designed a fuzzy logic EMAN for a grid-connected hybrid generation. The researched hybrid system includes an FC, ELS, and hydrogen storage subsystem. It can exchange electricity hourly with the power grid. PSO is the mobility and intelligence of swarms inspires a technique for optimizing that. PSO is inspired by the flight behaviour and information exchange mechanisms of birds. Examining the greatest population within a group that exhibits similar behaviour is critical. The PSO is a very resilient system [95]. Sayedin et al. [95] optimise the PV electrolyser (PV/EL) system using the PSO algorithm to minimize energy transfer loss. The proposed approach may be advantageous for directly connected PV/EL systems in various locations and climates. Marocco et al. [111] used the PSO technique to determine the component sizes that minimize the Levelized cost of energy (LCOE) for a stand-alone renewable Power-to-Power (P2P) system. MPC is frequently employed in the industry [113]. Fischer et al. [112] introduced an MPC for enhancing the economic performance of Power-to-Gas (P2G) systems. Fischer et al. [114] optimise the P2G conversion efficiency of a PEM electrolyser using MPC, in which a PEM electrolyser is situated in the German city of Freiburg. Morin et al. [113] examine the performance enhancements of an MPC-controlled RES. The results [112–114] indicate that implementing an MPC on a hydrogen storage system can result in significant cost savings and performance benefits.

Assessment of first top 10 most-cited articles on the hydrogen electrolyser field

This study determined the most impactful research initiatives currently underway by analysing the top ten papers with the highest number of citations from 2012 to 2022. Fig. 3(a) shows the first top ten article citation rates throughout the years. Early articles have greater citations than in recent publication years. Regardless of overall merit, earlier publications are referenced with greater frequency. Recently, high-impact publications may not have had enough time to accumulate citations. Table 1 shows that the top ten most referenced

Table 1 – A list of the top ten most-cited publications from 2012 to 2022.

Rank	Author's name	Ref.	Citation*	Target	Validation	Advantages
1	Samsatli et al. (2016)	[68]	113	A MILP model to optimise wind-hydrogen-electricity networks and reduce costs.	Validation is accomplished utilising gPROMS Process Builder and gCCS	The proposed hydrogen model used Mixed integer linear programming (MILP) to lower network costs in Great Britain.
2	Bareiβ et al. (2019)	[69]	89	PEM WE can reduce greenhouse gas emissions from transportation by up to 80%.	Data for the background system is from ecoinvent v3.3 and other sources.	Increase current density and reduce catalyst loadings while maintaining high efficiency.
3	Maroufmashat et al. (2016)	[70]	83	A mathematical model for effective EMAN and minimising construction and cost for energy hubs.	Validation is achieved utilising General Algebraic Modelling Software (GAMS).	Completion of an optimised urban energy network with energy hubs benefits from a distributed hydrogen energy production.
4	Mishra et al. (2012)	[118]	70	Utilising the BFO approach to tune the controller parameters in a suitable manner. GRC was used to model the controller of MG.	Validation is accomplished utilising MATLAB/Simulink.	Increase frequency excursion damping after each load perturbation
5	Guinot et al. (2015)	[119]	68	Optimizing of power management strategy and component size, and comprehensive component modelling.	Validation is accomplished utilising CEA made ODYSSEY platform.	Hybridizing batteries with a hydrogen system has several advantages. PV-Batteries-H2 is a more cost-effective than PV-Batteries configuration
6	Nojavan et al. (2017)	[96]	49	Find the ideal selling price to maximise the anticipated profit. Evaluate the difference between real-time and time-of-use pricing in a smart grid system to maximise its predicted profit in the real world.	Validation utilising time-of-use and real-time pricing cases.	A demand response program benefits both retailers (increased expected profit) and consumers (lower selling price)- a win-win strategy for both parties).
7	Bakhtiari et al. (2018)	[120]	48	A critical role of the hydrogen chain in lowering the cost of supplied energy.	Validation is achieved by the multi-criteria design procedure's performance.	ELSUB criterion helps contribute to further lower TEL, smaller WTs, and increasing community acceptance of the technology.
8	Aouali et al. (2017)	[121]	48	A PEM electrolyser model for hydrogen generation to evaluate electrical parameters under various operating conditions.	Validation is performed with MATLAB/Simulink.	PEM electrolysers are pollution-free and high-efficiency.
9	Ursúa et al. (2013)	[94]	47	Evaluate electrolyser performance in a stand-alone system with PV generators and wind.	Experiments on alkaline water electrolyser operating mode and other data were presented at the UPNa.	Achieved efficiency of over 70% on days with low and high variability.
10	Mendis et al. (2013)	[122]	46	Maintaining power balance of the RAPS system by restricting diesel generator to low load operation and wind generator to maximum power tracking mode.	Validation is performed with MATLAB/Simulink.	RAPS system can maintain voltage and frequency within tolerable limits. Maximizing wind power enhances the system's overall performance.

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publications were deemed to be the most significant works to date in hydrogen electrolyser research, hence indicative of general interests and trends in the broader field. Table 1 summarises the rank, author, citation, validation, and advantages. Table 1 shows citations to the top ten papers, ranging between 46 and 113, spanning 2012 to 2019. This study discovered that the publication contains a variety of targets and validations, all of which contribute to the research's benefits. Samsatli et al. [68], Bareiβ et al. [69], Maroufmashat et al. [70], Mishra et al. [118], and Guinot et al. [119] produced the top five articles, with citation counts of 113, 89, 83, 70, and 68, respectively.

Samsatli et al. [68] focus on research based on a MILP model for the design optimisation, operation, and cost reduction of integrated wind-hydrogen-electricity networks. The research has advantages, including the proposed hydrogen model utilising MILP to reduce Great Britain's infrastructure costs. The research conducted by Bareiβ et al. [69] aims to minimize GHG emissions from transportation by up to 80% by PEMWE. The background data is validated using ecoinvent v3.3 and other sources. The research demonstrates an advantage that allows for a rise in current density and a decrease in catalyst loadings while retaining a high efficiency level. Also, it should be highlighted that the review article by Bareiβ et al. [69], published in 2019 in Elsevier has garnered recent attention, indicating the importance and widespread concern surrounding this field. Maroufmashat et al. [70] focus on developing a mathematical model for effective EMAN and minimising the cost and complexity of EH construction. General Algebraic Modelling Software was used to validate the model of GAMS. The research shows the benefits of dispersed hydrogen energy production, such as an efficient urban energy network with the energy of hydrogen bonds (EH). Mishra et al. [118] presented two objectives: using the Bacterial Foraging Optimisation (BFO) technique to set the controller parameters resulting in an acceptable frequency excursion, and using generation rate constraint (GRC) to simulate the controller gains of MG. The method was validated using MATLAB/Simulink. The benefit of the research is increased frequency excursion damping following each load disturbance. Guinot et al. [119] study focus on power management strategy optimisation, component sizing, and complete component modelling. . This model is built on the CEA-developed ODYSSEY platform and demonstrates several advantages, including that PV-Batteries-H2 is more cost-effective than PV-Batteries. Additionally, papers ranked 6 and 7 emphasised on the critical role of the hydrogen network in lowering costs and maximizing profits in the system. Otherwise, papers ranked 8, 9, and 10 achieve high efficiency, is pollution-free, and improve overall system efficiency concerning the electrolyser.

Classification of study types of research

It is essential to identify study types while analysing the structure of top-ranked publications. The study type is an integral part of the study design and must be determined before the start of the study [123]. According to Table 2, the most frequently published type of study for top-ranked papers is the formulation of problems and simulations, with a frequency of 46 (38.3%), followed by a study of the state-of-the-

Table 2 – Classification of different study types for the most-cited papers.

Study types	Rank	References	Range of years	Range of years	Range of citation	Frequency	Percentage of frequency (%)
Formulation of problems and simulations	1, 3–6, 8, 10–11, 14, 17–19, 21, 23–25, 36, 41–42, 45, 50–51, 56, 61, 64, 66–67, 69–70, 74–77, 82–83, 86, 88, 91, 98–100, 107, 109, 118-120	[68,70,95,96,98,100–105,107–111,113,114,118,119,121,122,124–139[68,70,95,96,98,100–105,107–111,113,114,118,119,121,122,124–139,140–147]	2012–2022	2012–2022	1–114	46	38.3
Study of the state-of-the-art technology assessment	7, 13, 20, 26, 28, 29, 32, 33, 37–38, 43, 46, 48–49, 52, 54, 58–59, 63, 78–80, 84–85, 90, 92–96, 102–105, 112-116	[37,97,120,148–183]	2013–2022	2013–2022	1–48	39	32.5
Laboratory research, design, and performance evaluation	9, 12, 16, 22, 27, 30, 31, 34–35, 39–40, 44, 60, 62, 65, 68, 71–73, 81, 87, 89, 97, 101, 106, 108, 110–111, 117	[94,106,184–210]	2013–2021	2013–2021	1–47	29	24.2
Reviews	2, 15, 47, 53, 55, 57	[69,99,112,211–213],	2013–2019	2013–2019	14–89	6	5

art technology assessment, with a frequency of 39 (32.5%), laboratory research, design, and performance evaluation, with a frequency of 29 (24.2%), and reviews, with a frequency of 6 (5%). The distribution of published articles span a variety of years and citations but are all related to the subject of Energy and Engineering. This indicates that most research concentrated on problems and simulations, laboratory research, design, and performance evaluation, accounting for 62.5% of all studies, compared to 37.5% on state-of-the-art technical overviews and reviews. The formulation of problems and simulations receives the most attention from study types. In general, the topics addressed in the formulation of problems and simulations include hydrogen generating system model, mathematical model, numerical simulation, control strategy, and optimal operating strategy. The researcher is currently focused on the design, modelling, proposed controller method, optimum energy, and hydrogen management approaches for on- or off-grid PV or wind systems. Efforts have also been made to evaluate the performance of hydrogen electrolysers integrated using solar or wind energy in the power market. The findings emphasise the critical importance of hydrogen chains in lowering the cost of supplied energy.

These bibliometric studies also examine the subject areas presented in the top-ranked papers. Table 3 displays the classification of the top highest-ranking articles on the subject areas. The subject areas of electrolyser and hydrogen storage tanks with citation range 1–114 earned the highest frequency percentage (95%). The second position is the hydrogen production method with a citation range of 1–89, and a frequency weight of 69.17% and the third position is RE sources/PV/wind with a citation range of 1–114 and a frequency weight of 58.33%. With a frequency weight of over 40%, these subjects include economic perspective and benefits (54.17%), operational, simulation, and design optimisation (45.83%), grid electricity (42.5%), and energy storage technology (41.67%). The subjects observations shown in Table 3 are summarized as:

- Energy and hydrogen can be converted utilising existing production technologies (e.g. electrolysers (ELS), FCs, etc). Using an electrolyser, hydrogen can be generated from electricity and supplied to other hub cars or industrial needs as necessary [70]. The FC uses the electrolyser's stored hydrogen [124]. Hydrogen from electrolysers can be stored in caverns and pressure vessels. Subterranean pipelines transport electrolyser-produced or stored hydrogen to the fueling station [68]. Several electrolyser models and operating modes were described [119–121]. For instance, PEM and electrolysers (ELSs) [103,121,151,191,194,213], AEL [94,105,181] and hydrogen-generating Aqua Electrolyser (HAE) [102]. PEM is a very promising electrolysis technology [121].
- Because both fossil and RE can produce hydrogen, this hydrogen can help balance supply and demand in the power grid and reduce investment needs in grid expansion. Presently, 48% of hydrogen is produced from natural gas, 30% from heavy oils and naphtha, and 18% from coal [69]. Four basic production techniques are available: hydrocarbon pyrolysis, hydrocarbon reforming, biomass processing, and water splitting. Steam methane reforming (SMR) is commonly employed to reform hydrocarbons, whereas electrolysis is the most predominant method for water splitting. Electrolysis produces the lowest greenhouse gas emissions when the electricity used in the process is renewable [155,156]. The related papers [69,105] concentrate on hydrogen production for potential global climate change, whereas the related papers related hydrogen production for helping to balance the grid and reducing the cost of hydrogen [103,155,191].
- Regarding sustainability, the synergy between RE sources and hydrogen is essential [181]. PV and wind energies are ideal for integrating with electrolysers, considering their phenomenal development in power generation over the last ten years [94]. The number of wind and solar PV modules required to supply the community's energy demands with a RE source [99]. The primary concern with greenhouse gas emissions [104]. Solar and wind energy are naturally intermittent and unpredictable [122,210,213]. For WT selection, a specific application should be determined by load demand and system design [122]. All of these studies aim to boost the primary energy system's power output and reduce its storage size.
- Table 3 shows that researchers include various subject areas in their goals for enhancing the hydrogen electrolyser. Safety analysis for energy systems found the lowest frequency

Table 3 – Subject areas of hydrogen electrolyser field for the most-cited papers.

Subject area	Frequency	Range years	Citation range	Frequency weight (%)
Electrolyser and hydrogen storage tanks	114	2012–2022	1–114	95.00
Hydrogen production method	83	2013–2022	1–89	69.17
Renewable energy (RE) sources/PV/Wind	70	2012–2022	1–114	58.33
Economic prospective and benefits	65	2013–2021	1–114	54.17
Operational, simulation and design optimisation	55	2012–2021	1–83	45.83
Grid electricity	51	2013–2022	1–114	42.50
Energy storage technology	50	2012–2022	1–114	41.67
Wind-hydrogen-electricity networks	47	2013–2022	1–114	39.17
Control strategy	40	2012–2021	1–114	33.33
Experimental analysis/experimental hydrogen production	24	2013–2021	1–47	20.00
Hydrogen vehicle	21	2013–2022	1–114	17.5
Microgrid development	8	2012–2021	1–70	6.67
Greenhouse gas emission	6	2012–2021	9–114	5.00
Prototype with hydrogen power generation	5	2014–2019	6–43	4.17
Safety analysis for energy systems	4	2013–2021	10–39	3.33

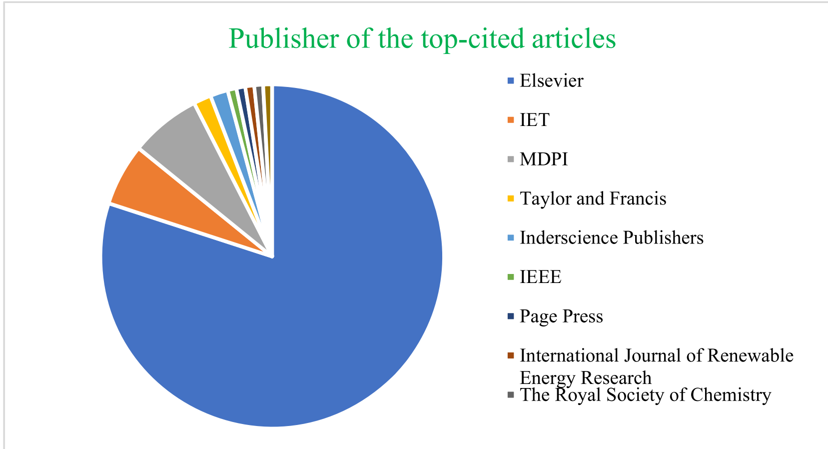

Fig. 4 – Publisher of the top-cited articles for hydrogen electrolyser.

weight (3.33%). Hydrogen safety concerns are mostly explored concerning the development of hydrogen electrolysers. Safety issues limit hydrogen electrolysers' development. The supplementary subjects are significant for hydrogen electrolyser research because they provide information and update on developments, which can lead to the development of the most advanced technology in this field.

Classification of subject areas of research

Fig. 4 examines the journal review according to the publishers. As depicted in Figs. 4, 10 distinct publishers were identified for the top journals. Elsevier published 80% of the top articles with high-quality publications. The Int. J. Hydrog. Energy from Elsevier is the most frequently reported (45%), followed by Energy Convers. Manag. (9.17%), Energy and J. Energy Storage contributed to the total (5%). The remaining journals, including Appl. Energy, Renew. Energy, Int. J. Electr. Power Energy Syst., J. Clean. Prod., Renew. Sust. Energ. Rev., Energy Build., Appl. Therm. Eng., J. Power Sources, Energy Rep., and Results Eng., contributed less than 5% of the total number of papers published. This illustrates Elsevier's publisher dominance in hydrogen electrolyser research [214].

Fig. 5 illustrates the most prominent articles published by ten distinct publishers. These papers appeared in 30 journals with IF values from 0.35 to 14.982. Typically, the IF is used to evaluate a journal's relative value, particularly in comparison to other publications on the same subject. When used to

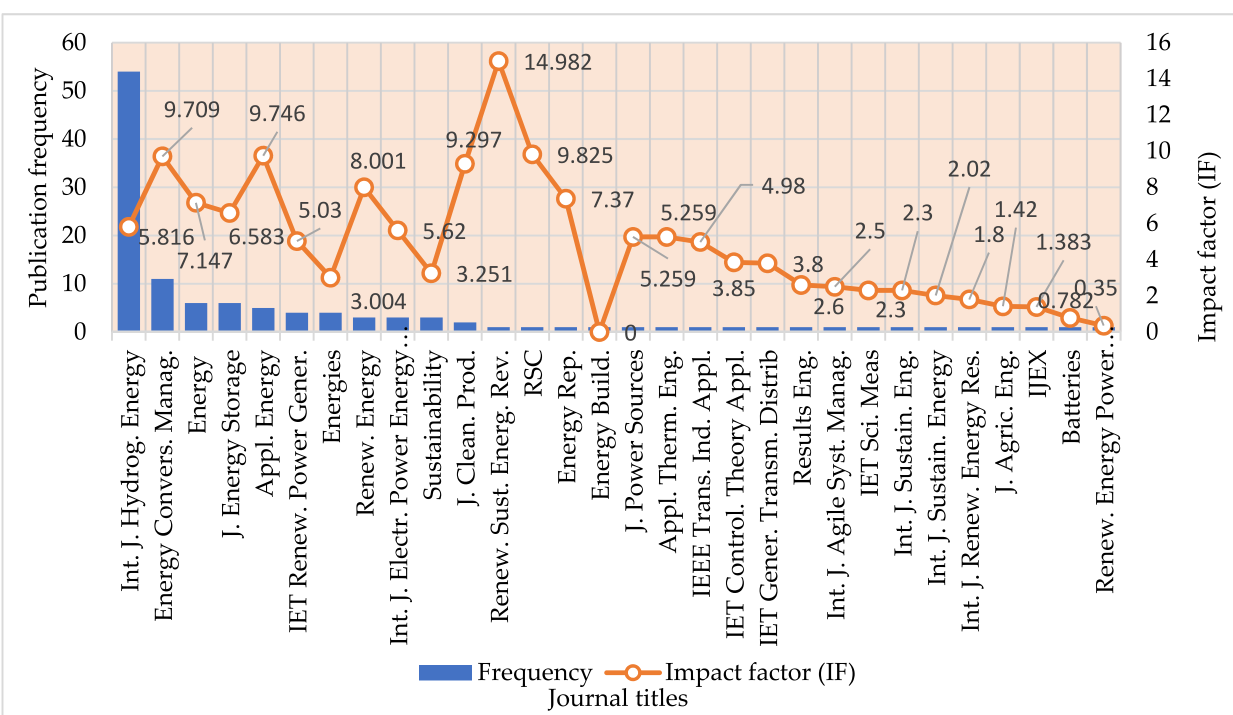

Fig. 5 – Articles for journal evaluation and impact factors.

indicate an article's quality, the IF of a journal will promote poor papers and demote good ones [214]. Fig. 5 indicates that the Int. J. Hydrog. Energy from Elsevier has the highest publication frequency with 54. The second-largest journal, Energy Convers. Manag. is published with a frequency of 11. The third most frequent journals are Energy and J. Energy Storage, each with a frequency of 6. Renew. Sust. Energ. Rev., Energy Convers. Manag., and J. Clean. Production had the highest IFs: 14.983, 9.709, and 9297. The frequency of hydrogen electrolyser articles published in Renew. Sust. Energ. Rev., Energy Convers. Manag., and J. Clean. Prod. is 1, 11, and 2, respectively. The most popular, however, targeted the top cited articles published in Int. J. Hydrog. Energy has an IF of 5.816. Six of the top ten ranked articles [68,70,94,96,119,121] were published in Int. J. Hydrog. Energy, which is published by Elsevier. According to Table 2, the articles ranked 1,3, 5, 6, and 8 [68,70,96,119,121] pertain to the formulation of problems and simulations, whereas research in the laboratory, design and performance evaluation pertains to the paper ranked 9 [94].

Keywords performances

This study focuses on the 15 most frequently used keywords contributing to the top-ranked articles to discover key research hotspots in the hydrogen electrolyser field. Fig. 6 indicates the top 15 most utilized keywords in the title and abstract field of all articles, ranging in frequency from 4 to 93. The different font sizes and colours indicate keyword frequency and rank. According to this figure, hydrogen (red) is the most frequently used favourable keyword with a frequency of 93. It is followed by electrolyser, renewable, solar, PV, optimisation, FC, and wind, with relative frequencies of 48, 30, 23, 22, 17, 11, and 10. In contrast, the frequency of the keywords control, water electrolyser, efficiency, electricity, economic, P2G, and microgrid is lower than 10. Noteworthy is the observation that the following keyword statistics from Fig. 6 have been used in titles or abstracts. Brauns and Turek [215] published a review paper of AEL papers from 1990 to 2019 that identified the keywords: renewable, solar, PV wind, electricity to gas, etc., were identified as favourable. After analysing keywords's findings in Fig. 6, it is important to highlight the following:

- Hydrogen is an energy carrier that must be generated through technological processes. Hydrogen and RE synergy is sustainable [61]. Water electrolysis produces renewable hydrogen efficiently. Water electrolysers can create hydrogen from PV electricity since their electrical characteristics match [72]. Hydrogen's energy and transportation uses are popular. Hydrogen can swiftly refuel automobiles and is created from RE and carbon-free nuclear energy [36,77]. Hydrogen generation based on RE can occur in standalone and grid-connected systems.
- Depending on the electrolyte type used, there are primarily three types of hydrogen-producing electrolysers: alkaline, solid polymer, and solid oxide [94]. AEL is the most well-established and commercialized technology due to its excellent technical performance and market. Demineralised water ensures module durability, lowers corrosion and electrochemical processes, and boosts process efficiency [94]. The parameters include powers, operating temperatures, pressures, and hydrogen flow rate factors [127]. The electrolyser-related keywords have been used in the top articles: alkaline water electrolyser [94,105,200], hydrogen generative aqua electrolyser (HAE) [102], methanol electrolyser [125], PEM electrolyser [127,153], electrolyser [122,145,149,201], PEV electrolyser system [132] and SOE electrolyser [202].
- Global recognition of RE has risen significantly year. RE market, innovations, investing structures and legislative frameworks have evolved rapidly [110]. Renewable hydrogen will undoubtedly be a future energy vector, as renewables will necessitate large-scale energy storage [135]. In recent years, RE generation technologies like WT and PV have advanced rapidly [97,135]. RES generate power for loads, while excess energy generates hydrogen to be

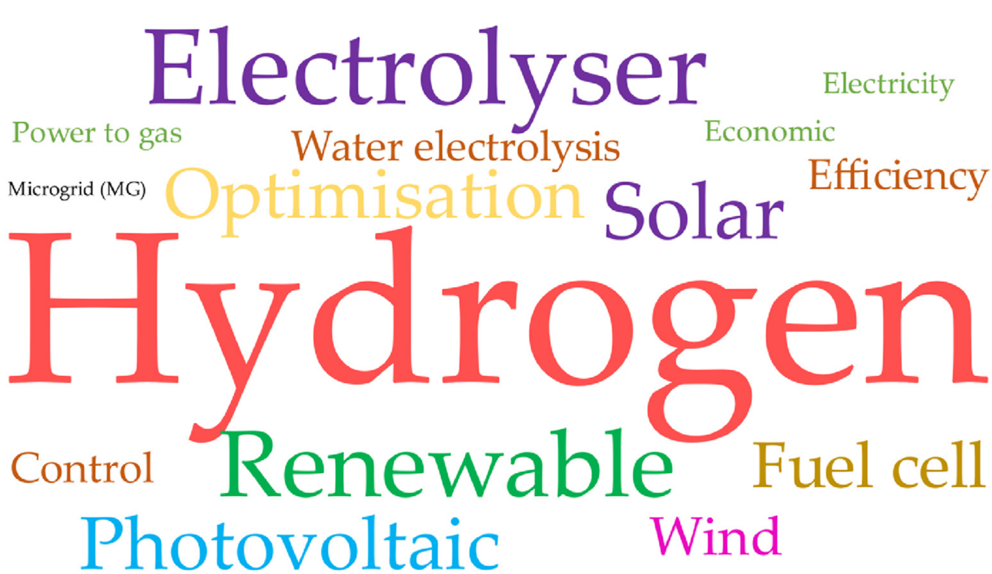

Fig. 6 – The top 15 most of keywords for hydrogen electrolyser research.

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used in FCs if renewables can't fulfil demand [97]. This study [97] suggests that RE hybrids are more reliable and cost-effective. "Renewable" keywords that highlight in the top cited articles are renewable hydrogen [94,135], renewable system [124], renewable energy (RE) [99,110,159], renewable storage [206], renewable [150,184] and renewable power [157].

- The other keywords that appear in the top the ranking articles, such as solar, PV, optimisation, FC, wind, control, water electrolysis, efficiency, electricity, economic, power to gas, and MG, are also substantial because they play a special role in facilitating the researcher in locating and retrieving information pertinent to hydrogen electrolyser. The keywords can also indicate the attempt to highlight what has been elaborated upon in publications, as well as the knowledge structure of the topic and the interrelationships between different fields of hydrogen electrolyser research.

Challenges and issues

This section highlights the issues and challenges based on the review results. Addressing these challenges will boost hydrogen electrolyser applications. The challenges and future development of the hydrogen electrolyser system which considered unpredictable and fluctuating electricity generated by renewable energy; modelling constraints; limitations in electrolyser's capacity, lifespan, and functionalities; high investment and operating costs; storage and safety concerns, and electrolyser efficiency, are summarized based on the analysis of top-ranking articles as follows:

Unpredictable and fluctuating electricity generated by RE

Green hydrogen from RES (solar, wind) is intriguing, but inconsistent and fluctuating electricity is a challenge [212,213]. Low solar irradiance or wind speed is cited as a difficulty for a solitary hybrid RES in the citation [120]. Electrolysis' versatility helps integrate renewables [69]. Provided with sufficient storage, excess hydrogen is used to stabilize future energy systems. Sophisticated electrolysis plants fed entirely by off-grid or on-grid solar PV or wind power plants with fluctuating and unpredictable electricity output also require additional evaluation. Modelling a dynamic electrolyser based on plant tests is important and needs to be looked into more in the future [216].

Modelling constraints for hydrogen electrolyser

For electrolysers modelling, common challenges include developing a physically-based model for estimating humidification in terms of pressure, current density, and temperature; modelling multi-phase transfer of species via current collectors and separator plates; and constructing a forecasting model for exchange current for catalysts. Modelling each component is crucial and must account for all operating situations. These conditions must be considered in the subsystem's characterization protocol [213].

Electrolyser's capacity, lifespan, and functionalities are constrained

According to the analysis of top-cited articles, it is noted that conventional electrolyser integration with RE emphasised commercial electrolyser restrictions, notably operational capacity and manufacturer-allowed stops. The operation is set to prevent dangerous hydrogen-oxygen combinations. It is possible to apply a strategy that electrolyser can remain operational for a given time whenever the module output drops underneath the lower working limit. Another strategy is to employ a battery bank to store excess power [181]. The storage system is designed to utilise the surplus power generated when the electrolysis module's nominal value is exceeded to boost an electrolyzer's availability when the electricity production displays its propensity to drop below the threshold.

High investment and operating costs

Pressurized alkaline and PEM installations have high investment and operating costs. Dael et al. [183] provide a summary of overall investment costs, capital expenses, and revenues. Based on their assessment for hydrogen production exclusively, i.e. electrolyser, production of hydrogen is economically feasible in 2050 with significantly more operating hours and lower investment costs. The electrolyser's business strategy can indeed be improved by producing H_2-based added-value compounds or liquid biofuels. Future techno-economic assessments should investigate how manufacturing elevated goods and bio-methane when lower energy prices boost profit motives.

Storage and safety concerns

Storage and safety issues of the hydrogen electrolysers technologies must also be addressed [8]. For efficient and safe operations, fuel cells must satisfy pricing, lifespan, and reliability criteria. The FC optimisation is vital, but so is industry restructuring. Innovation of FCs should be introduced effectively by trained professional services or experienced staff. Hydrogen's effectiveness in transportation would rely upon affordable FC vehicles. Furthermore et al. noted that the existing hydrogen storage technologies don't meet techno-economic feasibility; hence substantial hydrogen storage research is needed [71]. The security and reliability of hydrogen delivery to customers should be explored. Once establishing site plans, environmental constraints and ecological sustainability should also be considered [8].

Electrolyser efficiency

Currently, the effectiveness of water electrolysis systems is practically optimal. According to a report by Mekhilef et al. [217] AEL stack voltage efficiency is around 60%, proton exchange membrane electrolyser (PEMEL) is 50–60%, and solid oxide electrolyser (SOEL) is 60–80%. Thermal management of SOFCs can improve electrochemical processes, boosting efficiency [218]. Incorporating surfactants towards the working fluids or functionalizing nanoparticles may enhance nanofluid stabilization for PEM electrolyser [218]. The efficiency of a PEM system is anticipated to increase to between 67% and 74% [8]. To fully integrate RE, commercialized electrolyser technologies must have been improved. Reducing the electrolyser's lower working limit as well as improving the electrolysis stacks' resilience will enhance life span and efficiency. Additionally, academic researchers and enterprises must conduct increased R&D to enhance electrolyser feasibility and efficiency [217].

Conclusion

Due to rapid economic expansion, modernization, and environmental harm from fossil fuel consumption, the interest in establishing a clean and sustainable energy system has increased dramatically. In this context, the electrolysis of water has become increasingly popular due to the fact that it is environmentally friendly and has renewable chemical technology. Green hydrogen, produced by water electrolysis and renewable energy, is a promising fossil fuel replacement for achieving net zero by 2050. It provides a way to decarbonize industrial processes and commercial sectors as it generates no CO_2 and no air pollution when utilized. To investigate the development of hydrogen electrolyser, this study utilized bibliometric techniques based on the Scopus database focusing on current and highly referenced papers from 2012 to 2022. This research evaluated the history of the hydrogen electrolyser, evaluated the impact of hydrogen electrolyser analysis and its trend through a citation and bibliometric study, determined which topics attract researchers, identified the country with the most research activity and the journal with the most publications, and reviewed the most cited original works and literature based on the hydrogen electrolyser. The following is a summary of the most important findings from this bibliometric survey:

- As for the descriptive analysis, there has been a great growing demand spread worldwide for this topic over the recent years, from 2012 to 2022. The years 2018–2022 exhibited rapid growth, with a total of 67 publications, compared to the years 2012–2017, which saw a total of 53 publications. This represents approximately a decade's worth of the fastest-growing research in hydrogen analysis. The UK, Algeria, and France dominate research activity in engineering in the hydrogen electrolyser field.
- According to a classification of popular research topics, the top-ranking articles focused on the electrolyser and hydrogen storage tanks (frequency percentage of 95%), the hydrogen production method (frequency percentage of 69.17%), and RE sources/PV/Wind (frequency percentage of 58.33%). The investigation of research topics revealed that related issues complemented each other for the development of large-scale electrolysers. Green hydrogen will only be profitable if renewable energies are rapidly developed. The highly cited studies emphasised topic formulation and simulations, laboratory research, design, and performance evaluation for 62.5% of all studies, compared to 37.5% on state-of-the-art technical overviews and reviews.
- Prominent keywords in hydrogen electrolyser research include hydrogen, electrolyser, renewable, solar, photovoltaic (PV), optimisation, FC, and wind which are relevant tendencies. Three types of hydrogen-producing electrolysers are regularly utilized, depending on the type of electrolyte used: alkaline, solid polymer, and solid oxide. With multiple keywords, the study can provide extensive overviews of various applications.
- It was discovered that the research had been published in prestigious journals with an important influence on the outcomes. Hydrogen electrolyser papers published in Int. J. Hydrog. Energy, Energy Convers. Manag., Energy, and J. Energy Storage are accorded significant and extensive consideration by the researcher. Elsevier publishes all pertinent journals.
- As a summary of hydrogen technologies, alkaline electrolysis technologies are the most prevalent, but proton exchange membrane (PEM) and solid oxide electrolysis cells (SOEC) have also been developed. PEM electrolysers are more effective than alkaline and do not have the same corrosion and seal difficulties as SOEC, but they are more expensive than alkaline systems. AEL systems are the most advanced and have the lowest initial investment.
- According to an evaluation of high-quality articles, the frequency of control strategy studies is (33,33%). Most of these models are based on the equations correlating applied potential to current and hydrogen production in an electrolysis cell. MPC has gained popularity due to its ability to accommodate power constraints, ramp-ups, etc. The hydrogen electrolyser model and control design are scarce in the current literature.

In conclusion, despite the amazing global development of hydrogen energy, issues still exist which need further investigations. Industrial transportation and manufacturing are the most promising worldwide markets. The substantial rise of the hydrogen market demonstrates that confidence in developing hydrogen technology is quite good. The primary obstacles to the energy transition with hydrogen's crucial role in the future include fluctuation and unpredictability of electricity output from RES, necessitating more assessment and optimisation of electricity generation. Modelling constraints for hydrogen electrolysis and hydrogen insertion into the gas network increases management flexibility. It is required to find and create innovative methods for the generation and storage of green hydrogen, as well as to lower its costs, improve its production processes, and render the most economically and technologically sophisticated solutions safe and dependable. Modernization and breakthroughs in control techniques, low cost, high security, capacity, lifespan, functionalities, and efficiency are necessary to advance the hydrogen electrolyser, as the controller will facilitate its implementation. Green hydrogen can play a significant part in the world's energy transition if efforts remain coherent and synergistic. Thus, this study represents the initial step in mapping the modest research output across the hydrogen electrolyser field over the past decade. The outcome of this study could provide valuable insights and contributions to the growing hydrogen electrolyser development of the renewable and sustainable energy industry. Researchers from all nations should continue

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conducting research and contributing to the development of global knowledge. Future research on hydrogen electrolyser research papers should assess the multisource heterogeneous data using various analysis tools to evaluate the research papers' key findings. It is advised that in-depth research and reviews be conducted on integrating hydrogen with the multiple applications in the energy sector, safety, public policies, energy legislation, and prospective commercial opportunities associated with the hydrogen economy.

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.

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