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Investigating the evolutionary trends and key enablers of hydrogen production technologies: A patent-life cycle and econometric analysis

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HIGHLIGHTS

- Patent review on hydrogen production technologies from 2000 to 2019.
- Japan, US, China are the leading countries in the field.
- Recent developments are focused on renewable energy-based technologies especially water.
- Technology maturity rate of renewable-based technologies is about 57%.
- R&D expenditure strongly promotes hydrogen production innovations.

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ABSTRACT

With rapid industrialization, rising fossil fuel consumption, and environmental concerns, developing clean and green energy is an inescapable option. Hydrogen has emerged as a significant potential energy carrier and a viable future replacement fuel for fossil fuels due to its renewable and pollution-free properties. Previous review papers have significantly contributed to the body of literature on the various technologies for producing hydrogen by revealing key insights into their working principles and conditions, as well as the economic and environmental aspects. In addition, they also highlighted the potential pathways to enable the application of these technologies in the context of carbon neutrality. However, these studies have not broken down the evolutionary patterns and developmental progress of either fossil fuel-based or renewable energy-based technologies used to produce hydrogen. In addition, the currently available literature does not contain the most recent research that focuses on the evolution and life cycle of each technology category from a chronological point of view. The key drivers, countries/regions, and their contributions to

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Econometric analysis
Technology drivers

the field's development have received little attention. As a result, it is critical to monitor technological advances in hydrogen energy production and investigate the key enablers of these advancements. Against this backdrop, the current study employs patent analysis tools to achieve four primary goals: (1) to track the development trends in the field of hydrogen production from 2000 to 2019; (2) to identify and compare the recent development trends in the last five years according to the feedstock, i.e., fossil fuel, water, and biomass-based technologies; (3) to predict the technology life cycle of the two main groups of hydrogen production technologies (fossil and renewable); (4) to identify and compare the key drivers of hydrogen production technologies from a statistical standpoint. The findings of the study may aid in identifying technical prospects in the field of fossil and renewable-based hydrogen production, and decision-makers may use them as a reference in developing a strategic plan for future technological growth.

Introduction

The rapid expansion of global industrialization has resulted in a gradual depletion of conventional energy resources. In 2019, global energy consumption increased by 1.3% over the previous year to about 19 TW [1]. According to the International Energy Agency (IEA), fossil fuels accounted for more than 80% of the total global energy supply in 2018 [2]. Existing reserves would not be sufficient to fulfill future energy demands. The recently found reserves of oil, natural gas, and coal are anticipated to last less than 40 years, 60 years, and 250 years, respectively [2,3]. In addition to the depletion of these resources, their excessive consumption negatively affects the environment. Global energy-related carbon dioxide (CO_2) emissions totaled 3.31 billion tons in 2018, the highest amount on record, according to the International Energy Agency [4], and no decreasing pattern is expected soon. In 2018, global CO_2 was 407.8 ppm, methane was 1869 ppb, and N_2O was 331.1 ppb [5]. Furthermore, these harmful gaseous pollutants harm human health by causing asthma, respiratory problems, strokes, heart attacks, and premature mortality [6].

Most countries have recently made significant efforts to reduce greenhouse gas emissions, such as carbon dioxide, to avoid global warming and rapid climate change and to ensure a safe and clean environment [7,8]. Now renewable energy sources, such as solar [9], wind [10], hydro [11], biomass [12], and geothermal [13], have received extensive attention. Renewable energy is typically regional, unsustainable, and challenging to store and transport. On the other hand, hydrogen energy is considered one of the most promising energy sources due to its great efficiency and cleanliness - hydrogen is a renewable gas with high energy efficiency, making it a viable alternative for a carbon-free environment [14]. Hydrogen is regarded as the most appealing renewable energy in the twenty-first century. It has tremendous potential to be used in key fossil energy-consuming sectors due to its diverse sources, high calorific value, good thermal conductivity, and high reaction rate [15]. The history of hydrogen and energy can be traced back over two centuries. The first demonstrations of water electrolysis and fuel cells captivated engineers in the 1800s [16]. Hydrogen was used to power the first internal combustion engines over 200 years ago. Hydrogen-powered balloons and airships propelled humanity to the moon in the 18th and 19th centuries and the 1960s [17]. The production and distribution of hydrogen have evolved into a global business. Demand for hydrogen and hydrogen-based products has increased by more than 300% since 1975, and the IEA predicts that demand will continue to rise as new applications emerge [18]. Fig. 1 illustrates the annual demand for hydrogen in its pure form since 1975 [17]. The widespread use of hydrogen in clean energy systems is gaining popularity due to two factors: 1) it produces no direct emissions of air pollutants or greenhouse gases, hydrogen combustion theoretically produces only pure water [19,20]; and 2) it can be produced using a variety of low-carbon energy sources [17]. Renewable electricity, biomass, and nuclear power are all feasible options for producing clean hydrogen. Low-carbon fossil-based hydrogen production is also possible if combined with carbon capture, utilization, and storage (CCUS) while reducing emissions from fossil fuel extraction and supply [17].

According to the IEA, the demand for hydrogen in 2020 stood at ~90 Mt, where nearly 80% was used as pure hydrogen and the remaining mixed with carbon-containing gases for manufacturing steel and producing methanol [21,22]. In the Net Zero Emissions (NZE) scenario, hydrogen demand is expected to be nearly six times that of 2020, reaching 530 Mt by 2050. The industry and transport sector will share about 50% of this demand. In comparison, the industry's hydrogen demand will triple to around 140 Mt in 2050 from 50 Mt in 2020, while transportation's demand will rise from less than 20 kt in 2020 to more than 100 Mt in 2050 [23]. In this context, the ever-growing demand for hydrogen has led to a substantial evolution of the field in recent years, ushering in a new era and contributing to the design of future energy infrastructure. According to the International Renewable Energy Agency (IRENA), hydrogen is produced from various sources, with roughly 95% coming from fossil-based fuels, including oil, natural gas, and coal [24]. However, by 2050, the share of water (electrolysis) and biomass might rise to 30% [25]. As a result, hydrogen is presented as a viable zero-emission, infinitely renewable resource, capable, and cost-effective cleanest fuel for current and future energy demands [25]. Until recently,

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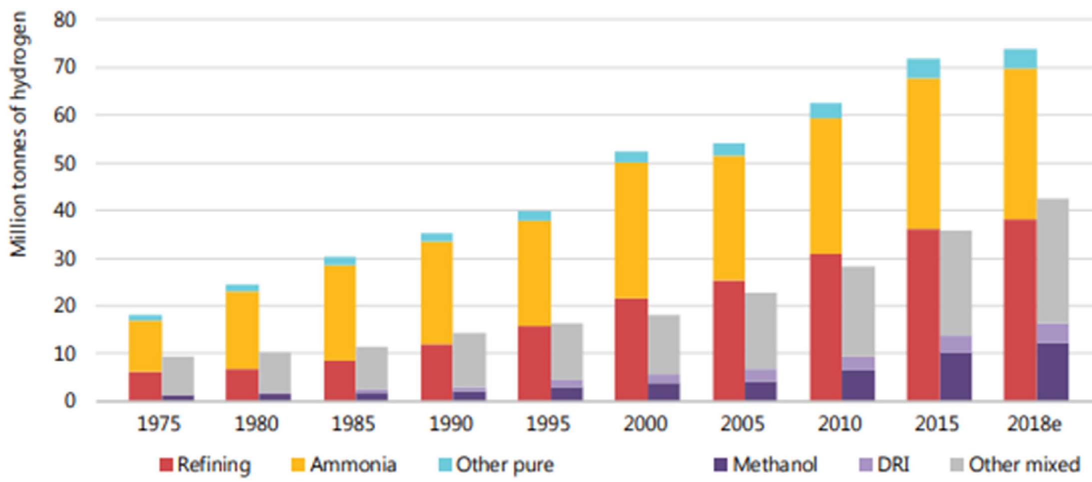

Fig. 1 – Global demand for pure hydrogen 1975–2018 [17].

several hydrogen production technologies have been developed. Steam reforming, partial oxidation, and gasification can all be used to produce hydrogen from fossil fuels [3,26]. Hydrogen production from renewable sources includes but is not limited to biomass gasification and water splitting utilizing solar, wind, or nuclear energy [27].

Previous studies have extensively reviewed hydrogen energy from fossil fuels and renewables [28–36]. However, there are some general limitations to these studies. The above-cited studies are conventional reviews often characterized by subjectivity depending on the authors' experience level in the field. In traditional review articles, it is challenging to organize quickly, thoroughly summarize, and quantitatively assess a certain subject's development trend and characteristics across a vast number of studies over a long period [37]. In addition, these types of articles require a narrow scope of research and thus, tend to include a lesser number of papers for review, e.g., between tens (e.g., 40) and low hundreds (e.g., 100–300) [38]. They could also be marred by interpretation bias from scholars across different academic backgrounds [39]. As such, the use of modern review methods such the bibliometric analysis for investigating the evolutionary nuances and research characteristics of a field has seen significant growth in the field of energy and environmental science, of which hydrogen energy is no exception. Based on 1275 documents across 218 journals, Kar et al. [40] mapped the research field of hydrogen economy over the last 50 years. Sillero et al. [41] used 3071 documents from the Web of Science © database to investigate the global research trend and characteristics of hydrogen production from dark fermentation. 22,612 documents published from 1900 to 2019 were used to conduct a bibliometric analysis on hydrogen storage by He et al. [42]. The research nuances and hotspots in hydrogen safety based on relevant publications from 1957 to 2021 have been studied by Wei et al. [43]. Nabgan et al. [44] reviewed the research field on catalytic biohydrogen production from organic waste materials through literature review and bibliometric analysis. According to Scopus-based literature over the last two decades, advances in hydrogen production from food waste have been presented in the work of Sridhar et al. [45]. Zhao et al. [46] have used bibliometric and content analysis to map the research field of hydrogen production using microbial electrolysis cells. Despite making a significant contribution to the literature, these studies lack discussions on the current state of the field, technological development patterns, key actors (countries/regions and assignees), and future possibilities from the perspective of technological innovation. Furthermore, none of these studies monitors the influence of the several innovations made in the field. Also, to the best of the authors' knowledge, these studies hardly review the latest innovations in the area of hydrogen production for both fossil fuel and renewable-based production methods. In addition, the technological life cycle and assessment of hydrogen production technologies is clearly missing in these studies, i.e., at what stage of development are the various technologies, their technology maturity rate, and saturation characteristics. To fill these gaps in research on hydrogen production technologies, patent analysis tools are deemed fit.

Patent analysis has long been recognized as a valuable tool for technology monitoring because it can represent innovation's current and historical development in a specific technological sector. Common analysis applications include the study of technological trends, the identification of important technologies, the research of new technologies, and the forecasting of technological progress. Over the years, the use of patent analysis has been witnessed in the field of hydrogen energy. Hwang et al. [47] investigated the technology trend for water electrolysis. Noh et al. conducted a patent analysis to reveal the technological characteristics of hydrogen storage and its technology [48]. Similarly, Chanchetti et al. [49] adopted patent indicators to forecast technologies related to hydrogen storage materials. Chen et al. [50] performed a patent analysis that considered hydrogen energy and fuel cell technologies. Technologies for fermentative hydrogen production from biomass have also been investigated by Hsu et al. [51]. In a more recent study, Martinez-Burgos et al. [52] investigated the current developments in the field of renewable hydrogen production technologies. The application of hydrogen technologies in the automotive industry from a technological trajectory point of view has also been investigated by Rizzi et al. [53]. Olivo et al. [54] conducted a patent analysis in the area of advanced biohydrogen technologies. The reviewed studies have made important additions to the development of the field – however, they are not spared from limitations as well. Some of these studies were conducted more than a decade ago [47,48,50,54], and do not qualify for revealing the 'latest' trends in a 2022 assessment. In addition, some of these studies are more specific with regards to the hydrogen production source. In other words, these studies only focus on one source of hydrogen production; renewables [47,51,52,54] instead of a holistical review of all hydrogen sources (including fossil-based sources). Others have rather focused on further stages of the hydrogen supply chain such as storage [48,49] instead of production. Also, the industry of application has been specific for some of these studies, for example, the automotive industry [53]. According to the discussions above, significant research gaps must be filled sooner rather than later. To fully understand the development and direction of this field, more work is needed to forecast future technological trends, identify promising innovative and technological competitors, and identify technological hotspots and vacuums. Against this backdrop, the current review examines the field's technological development from 2000 to 2019. The field's key innovators/assignees, countries/regions, and novel technologies are thoroughly discussed. Also presented in this study is the technology life cycle of various hydrogen production technologies. Furthermore, a comparative trend analysis of fossil-based, water-based, and biomass-based hydrogen production patents in the last five years has been conducted.

In order to fully understand the development and direction of the technological growth of this field, studies should go beyond technological trends, key innovators, and their country of origin - the driving forces behind the development need to be revealed alongside. The above-reviewed papers on patent analysis related to hydrogen energy, as part of their identified research gaps, have failed to consider this aspect of technology determinants in their analysis. Econometrics is the quantitative application of statistical and mathematical models to data in order to generate theories or test hypotheses in economics and forecast future trends based on historical data. It performs statistical tests on real-world data before comparing and contrasting the results to the hypothesis or ideas under consideration. Previous studies have made significant efforts to account for the driving forces behind technological growth and innovation. Li et al. [55] utilized econometric research to see if a country's current knowledge base is technologically relevant to the growth of renewables and if international knowledge spillovers assist it in developing renewable energy technologies. Spatial characteristics and the driving factors of low-carbon energy technology innovation in China were also conducted by Zhang et al. [56]. Similarly, the driving forces for low carbon technology innovation in the building industry were critically reviewed by Lai et al. [57]. Based on four main dimensions, the enablers for innovation activities across Europe were assessed by Corsatea [58] with wind, solar, and bioenergy technologies as evidence. In an earlier work, Brunnermeier and Cohen [59] presented novel findings on the determinants of environmental innovation in US manufacturing industries. Fujii and Managi [60] used patent application data in a decomposition analysis framework to assess four driving factors of Japan's environmental technology development. Due to the identified research gap mentioned earlier, as part of the current study's novelty, econometric tools are adopted to statistically ascertain the key determinants of hydrogen production technologies.

Because the scientific community, corporations, and governments are all interested in perfecting the transition from fossil fuels to clean fuels like hydrogen, this research aids in making more informed judgments on where to allocate financial resources and efforts. The study's findings may aid in identifying technological opportunities in the field of hydrogen production and act as a guide for decision-makers in developing a strategic plan for future technological growth. The remaining parts of the current review are as follows. Literature review on patent analysis reviews the extant studies of patent analysis in the field of energy and environmental sciences. The various methods used to gather data for the current study are discussed in Patent analysis: research methodology. By way of patent analysis, the key actors, the evolution, trends, core technology areas, and market focus in the field are comprehensively reported in Results and discussion. Enablers of hydrogen production technologies presents statistical findings on the enablers of hydrogen production technologies using econometric models. In Summary of significant findings, significant findings of the current investigation have been distinguished and summarized. The key challenges, future perspective, summary, and recommendation on the studied topic conclude the current work in Key challenges and future perspective on hydrogen production and Conclusion and recommendations.

Literature review on patent analysis

Patent analysis has been successfully employed in several studies to track and monitor the evolution of technologies in several fields of science. In recent years, the tool has gradually gained popularity in the field of energy and environmental sciences. In this section, previous related patent studies in the field are reviewed, and some of the key findings from each study are summarized.

Mao et al. [61] examined 11,840 patents relevant to industrial wastewater treatment systems using a mix of patent analysis and text mining (IWT). Their results showed that China ranks top in the number of related patent publications. Their study identified technologies related to method, device, material, and associated industry as hot themes. According to the study's findings, research into physical treatment devices, advanced oxidation processes, and automated and energy-saving treatment systems are the most promising areas in the near future.

Li et al. [62] investigated previous patenting projects in the area of Offshore liquified natural gas (LNG) storage and transportation. The top five patenting countries were determined to be South Korea, the United States, China, France, and Japan. LNG storage, LNG terminals, heat exchange and cold energy usage, LNG regasification, and LNG transportation were among the five technical areas identified by cluster analysis. In the LNG storage and transportation domain, these technologies provide the foundation for development.

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The work of Ma et al. [63] examines patents for electric vehicles (EVs) from 1970 to 2016. According to them, overcoming the challenge of safely and rapidly charging a battery through a charging facility and distributing the energy to each storage unit is a hot topic in the world of EV technology, involving battery, charging facility, and power control system technology. Wireless charging technology is the EV technology's research frontier.

Patent filings in Brazil on ways to reduce pollution emissions from agricultural machinery engines were analyzed by Silveira et al. [64] using patent analysis. John Deere and Cummins were acknowledged for their significant engagement in the agricultural machinery sector and for being among the top 30 firms in Brazil with the most patents published. The Y02T-10/24, which describes the Selective Catalytic Reduction system used to decrease NO_X, was unveiled as a core technology. Another technology discovered was the Y02T-10/144, which aims to improve engine performance by using a turbocharging system and extending its life.

Sinigaglia et al. [65] have researched the development of internal combustion engines (ICE). According to their findings, the internal combustion engine had a technology maturity rate of 81.77% in 2018. Water injection, friction loss, and hybrid technology are the sub-technologies with the fastest diffusion rate among those compared. According to their projections, internal combustion engines will reach saturation in terms of patent families in around 27 years. In the short to medium term, the technologies likely to provide significant technological advances in internal combustion engines are integrated exhaust manifolds, refrigerated exhaust gas recirculation, variable geometry turbochargers, variable valve lifting pre-combustion system chamber, cylinder deactivation, variable compression ratio, and water injection.

Patent citation analysis was used by Li et al. [66] to track the technological transfer of battery-electric cars in China. They discovered that while technology transfer networks have become more complicated over time, technology transfers across firms have been unequal. More crucially, large vehicle manufacturers and newcomers have a significant role in technology transfer, followed by leading automotive suppliers, with universities making a minor contribution.

Severo et al. [67] investigated the state-of-the-art of microalgae photobioreactors incorporated into combustion processes using a technological mapping based on a patent survey. According to their work, North America, China, India, and the European Patent Office (EPO) are at the top of the list for microalgae processes integrated with energy-based systems, such as combustion or heating. GreenFuel Technologies Corporation is the most innovative firm in the area. The company holds two major patents dealing with microalgae culture and fossil fuel emissions to make biofuel. Their findings also suggest that the corporations' patent portfolios are mostly focused on biotechnology and environmental technologies.

Lee [68] has mapped the impact of artificial intelligence on electric car technological advancement through patent analysis. More innovations from the field of self-driving automobiles, as well as traffic control system technologies, have been applied to EV technology. Since 2011, charging system optimization, self-driving car technology, and traffic control system technology have been widely applied to electric vehicle technology, and this has been attributed to the development and growth of deep learning algorithms after 2011 and extensively applying algorithms to electric cars.

Yuan and Li [69] have also mapped the technology diffusion of battery electric vehicles (BEV) based on patent analysis. Three key conclusions emerge from their investigation. To begin with, the development of BEV technology is centered in five countries: Japan, China, the United States, Korea, and Germany. Second, the markets for securing innovations tend to be concentrated, with China, Japan, the United States, and Europe as the most important. Third, global technological diffusion is unequal, focusing on the core group. There is a strong closeness between China and the United States for the transmission of BEV technology, as well as between China and Germany.

To have a better understanding of nuclear waste management technology, Suh et al. [70] conducted a patent study. The findings reveal that geographical factors such as nuclear weapons history, ideology, geological circumstances, resource availability, and international affairs have a significant impact on nuclear waste treatment technology trends. They discovered that the majority of technological progress is focused on long-term storage. European countries and the United States choose geological disposal, but Japan has made significant efforts to recycle all plutonium.

Based on patents, Yin et al. [71] assessed technological cooperation in carbon capture and storage (CCS). They discovered that the United States files the most CCS patents, followed by Japan and China, indicating that these three nations are the most active in CCS technology innovation. Further findings indicated that American and Japanese firms have a strong presence in the field of CCS and have considerable technological advantages.

Leng et al. [72] recently investigated technology innovation in China's rare earth sector. According to the findings, technologies represented by the development, extraction, and smelting of rare earth resources are the key players in the innovation network and serve as the power and control center of the technical innovation network in terms of individual networks. Further analysis reveals that China's innovation environment, followed by research and development (R&D) expenditure and resource retention capacity, is the most important driving force for technology innovation in the rare earth industry.

Spreafico et al. [73] bibliometric study of patents and papers reveals the evolution of pyrolysis technology. The findings of this study show that the time distributions of annual publications related to various pyrolysis technologies, both in relation to the various processed materials and on a global level, revealed a unified interest in the fluidized bed and hot balls, with net growth that began about twenty years ago and has remained constant in the last decade, while plasma and laser are still in the embryonic phase, with growth that is yet to begin.

Table 1 summarizes the extant literature on patent analysis in the field of energy and environment, highlighting their titles, period of investigation, databases(s) used, and total dataset analyzed.

Table 1 – Description of extant literature.

ID	Area	Period	Dataset	Database	Reference
1	Industrial wastewater treatment	1973–2020	11,840	Derwent Innovations Index	[61]
2	Offshore LNG storage and transportation	≤2020	689	Derwent Innovations Index	[62]
3	Electric vehicles	1970–2016	131,007	Derwent World Patents Index	[63]
4	Agricultural machinery engines	2006–2017	134,780	Questel Orbit Platform	[64]
5	Internal combustion engine vehicle	1980–2018	7037	Questel Orbit Platform (USPTO)	[65]
6	Battery electric vehicles	1985–2019	24,862	Derwent Innovations Index	[66]
7	Microalgae photobioreactors	2000–2020	3580	Questel Orbit Platform	[67]
8	Artificial intelligence in electric vehicles	1980–2017	3104	Korea Intellectual Property Rights Information Service	[68]
9	Battery electric vehicles	1985–2019	24,862	Derwent Innovations Index	[69]
10	Nuclear waste management	1972–2014	5614	WIPSON	[70]
11	Carbon capture and storage	2007–2017	3206	Derwent Innovations Index	[71]
12	China's rare earth industry	1967–2020	59,984	Derwent Innovations Index	[72]
13	Pyrolysis technologies	≤2020	42,599	ORBIT	[73]

According to the above literature review, there is an increasing use of patent analysis to track and investigate the development and trends in the environmental, energy, and power research fields. The tool has proven to be extremely useful in determining which areas of a specific field are the most developed, developing, niche, emerging, and declining. Researchers have also used patent analysis over the last two decades in the field of hydrogen energy. Chanchetti et al. [49] adopted patent indicators to forecast technologies related to hydrogen storage materials. Their results reveal that the main patenting territories were the USA, Japan, China and the European Union. For patents originating from the USA, the main classes of hydrogen storage materials were made of simple hydrides and borohydrides. Chen et al. [50] performed a patent analysis that considered hydrogen energy and fuel cell technologies. The researchers claimed that at the time of their investigation, hydrogen production and storage technologies were yet to reach the maturity stage whiles fuel cell technologies were already passed technological maturity. Technologies for fermentative hydrogen production from biomass have also been investigated by Hsu et al. [51]. The researchers developed five scenarios for commercial applications of biomass fermentation for hydrogen production, including the screening and cultivation of hydrogen-producing bacteria with high hydrogen production yields, the production of hydrogen/methane or other economically valuable products via fermentative hydrogen production processes and devices, and the use of waste material/all kinds of biomass materials/treated waste water as potential feedstock sources. In a more recent study, Martinez-Burgos et al. [52] investigated the current developments in the field of renewable hydrogen production technologies. In this study, it was found that amongst the investigated routes of renewable hydrogen production, only electrolysis is at the commercial stage and the advances in this area are related to electrodes and new catalysts. The application of hydrogen technologies in the automotive industry from a technological trajectory point of view has also been investigated by Rizzi et al. [53]. It has been revealed that the growth in electric drives determines the success of fuel cells and storage technologies. Significant attention was given to storage technologies as innovators attempted to tackle issues related to the availability of hydrogen refueling stations for hydrogen ICE vehicles and fuel cell (FC) vehicles. Also, inventions related to FC were relatively higher than those of hydrogen ICE. Olivo et al. [54] conducted a patent analysis in the area of advanced biohydrogen technologies. This study found China as the biggest patent contributor in the field. However, the developments in the field are highly concentrated in academic institutions, with few of their patents patented at the international level - thereby decreasing their competitiveness.

However, as discussed in Introduction, the above-mentioned studies have general limitations, and gaps in research should be filled sooner rather than later. The current work aims to provide the most recent developments in the field of both fossil-based and renewable-based hydrogen production technologies, reveal the lifecycle of the technologies in the field dating back six decades, and, finally, analyze the key enablers behind the field's development using econometric tools.

Patent analysis: research methodology

From the 18th of January 2022 to the 1st of March 2022, the Derwent Innovation Index (DII) was used to gather patent documents on the reviewed subject. Over 50 patent granting authorities are indexed in the database, which provides unique value-added patent information. It is a large database that contains information on over 39.4 million patent families and updates its data on a regular basis. Since 1973, it has also included references and citations from six main patent-issuing authorities (PCT-Patent Cooperation Treaty, US, Europe, Germany, the United Kingdom, and Japan). It also includes patent citations, allowing for tracking of an innovation's impact in a certain sector. The current patent analysis is approached from three directions. In the first instance, the overall output and trend of the field of hydrogen production from 2000 to 2019 are investigated and presented. In the second instance, a comparison of the patent developments in the last five years according to the feedstock used in the hydrogen production process is investigated and presented. Also, the technology life cycle and assessment of the two main types of hydrogen production technologies are

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analyzed. The search approach from the two instances was purposely varied. The search strategy employed in retrieving relevant patent documents is described below.

Global overview

Following the strategies of previous studies [61,62,74,75], for the overall output of the field, we decided to go with the search query based on generic terms and synonyms for ‘hydrogen production’ instead of the technical names of the various production technologies which were reserved for subsequent analysis. The search terms are herein presented: Topic (TS) = (“producing hydrogen” OR “hydrogen production” OR “generating hydrogen” OR “hydrogen generation”) AND International Patent Classification (IPC) = (B01* OR C01* OR G05* OR G21* OR H01M* OR H02*) were entered in the DII database with a customized timespan from 2000-01-01 to 2019-12-31. To reduce data pollution as high as possible, the search strategy was modified to include IPC that are expected to be assigned to patents within the scope of the current review. B01; Physical or chemical processes or apparatus in general: C01; Inorganic chemistry: G05; Controlling/regulating: G21; Nuclear physics/nuclear engineering: H01 M; Processes or means: H02; Generation, conversion, or distribution of electric power. A total of 10,097 patent documents were initially obtained. At the discretion of the investigators, the search was refined to include documents only recorded in the subject area of “Energy fuel” due to the scope of the current study. The process resulted in a final dataset of 6103 patent documents, which were downloaded in.txt format and exported into ITGInsight [76], a powerful text mining and visualization tool for further data cleaning, refinement, and analysis. After cleaning and refining, a final dataset of 6041 patents was used to generate the results. Data visualization has been done via VOSViewer © and Originlab2022 ©.

Technology-specific overview

To conclude the patent analysis, the search query was modified to obtain a comparative analysis of the latest trends in the various technologies. Based on the feedstock, the technologies were classified into three − fossil fuel-based technologies, water-based technologies, and biomass-based technologies. An analysis of DII patents within the last five years was made. This not only highlights the field's current status but also provides valuable insights as to what could be expected in the near foreseeable future. Accordingly, the search query was restricted to patents published in the last five years, and the keywords are specified herein: Fossil fuels − TS = (hydrogen AND "steam reform*") OR (hydrogen AND "partial oxidation") AND (hydrogen AND "autothermal reform*") OR (hydrogen AND "coal gasif*") OR (hydrogen AND "hydrocarbon pyrolysis"); Water − TS = (hydrogen AND electrolysis) OR (hydrogen AND thermolysis) OR (hydrogen AND photolysis); Biomass − TS = (hydrogen AND bio-photolysis) OR (hydrogen AND "dark ferment*") OR (hydrogen AND "photo ferment*") OR (hydrogen AND "biomass pyrolysis") OR (hydrogen AND "biomass gasificat*") OR (hydrogen AND "biomass combust*") OR (hydrogen AND "biomass liquefaction"). The subsequent processes after obtaining the initial results are the same as the steps outlined in Global overview. A total of 1971 patent documents were obtained for this part of the analysis.

Technology assessment and life cycle

The initial stage in technology planning is technology forecasting. Technology forecasting leads to the identification of opportunities and the direction of technological advances [77]. As shown in Fig. 2, every technology has a life cycle that is separated into four stages. The S-curve depicts the evolution of innovation, from its slow start as the technology or process is developed, to an acceleration phase (a steeper line) as it matures, and finally to its stabilization over time (the flattening curve), with corresponding increases in the performance of the item or organization that uses it. Technology eventually reaches its technological limit of utility or competitive advantage. At any time, there may be a technological breakthrough — a radical innovation − resulting in a new S-curve.

The search query in this section was restricted to patents published from 1966 to 2019, and the keywords search and filter are the same as that of Technology-specific overview. In general, the Gompertz and Logistic models are the most extensively used approaches for fitting S-curves [79] and outperform the other models [80]. Following the work of Chen et al. [50], the Logistic curve model was used to study the growth curve S in the current study. We utilized Loglet Lab 4, which is created by Rockefeller University in 1994 and is a program used for this type of forecasting analysis. The Logistic curve's primary coefficients were determined using Monte-Carlo iterations.

Three metrics may be calculated to describe the pace of patent development. The technological maturity rate (TMR) Equation (1), the estimated remaining life (ERL) Equation (2), and the number of prospective patents to appear (PPA) Equation (3), are these indicators [81]. The first and third indicators are easily determined using the growth curve's saturation level k. The TMR has a value between 0 and 1 and represents how close a technology has reached its maximal level of development. When the TMR crosses the 0.5 development range, the technology has reached maturity [82]. ERL is used to estimate how much time it will take to attain saturation. A technology's TMR, ERL, and PPA are defined as follows [83]:

$$TMR(t) = \frac{k_{now}}{k} \tag{1}$$

$$ERL = T_k - T_{now} \tag{2}$$

$$PPA = k - k_{now} \tag{3}$$

where k_{now} represents the cumulative number of patents at time t, T_k is the year that the cumulative number of patents is expected to reach saturation, and T_{now} is the present year. The above methodology has been followed from Sinigalaglia et al. [65].

Results and discussion

Technology output and geographical distribution

Fig. 3 shows the annual development of hydrogen production technologies. Patent activities in the field are growing at an

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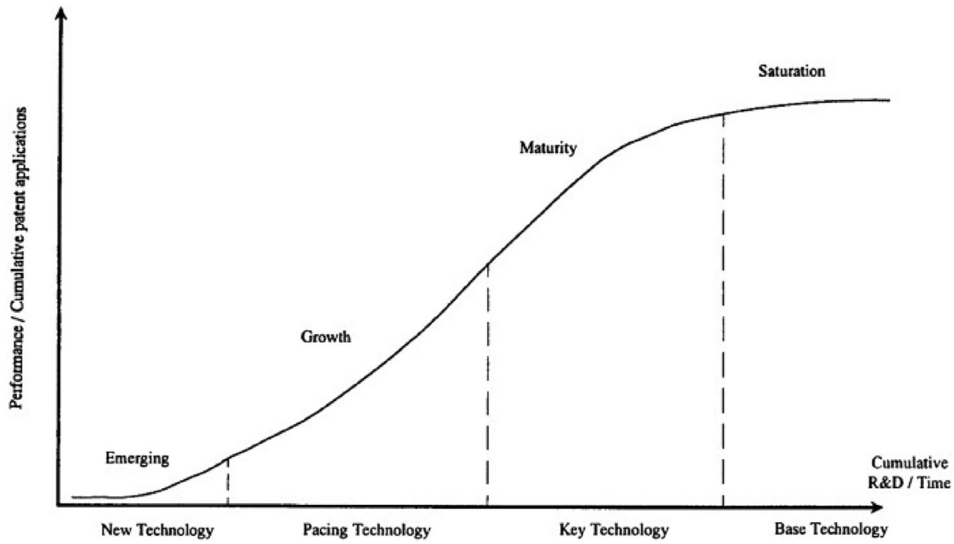

Fig. 2 — Technology life cycle diagram [78].

average annual rate of 4.21%. The five most productive years for patent activities have been 2006 (390), 2015 (386), 2005 (375), and 2004 (372). With respect to growth rate (with respect to previous year), the order varies as 2015 (+65.67%), 2001 (+59.42%), 2002 (+40.45%), 2003 (+10.03%), and 2004 (+9.41%). IEA reports that between 2005 and 2011, governments across the globe had allocated at least USD5 billion for research, development, and demonstration of hydrogen fuel, which is about USD1.5 billion more than what was allocated in the period of 2012–2018 [84]. This could explain the relatively high patent activities in the first half of the study period in contrast to the second half. In Fig. 4, we look at the relationship or degree of consistency between the number of patent applications per year in contrast to innovators, assignees, and countries/regions. It can be seen that the main peaks for patents filed, innovators, or assignees occurred in 2006 whiles that of countries/regions occurred a year later. Also, it is observed that the activities in the field with respect to patents, innovators, assignees, and countries/regions have largely

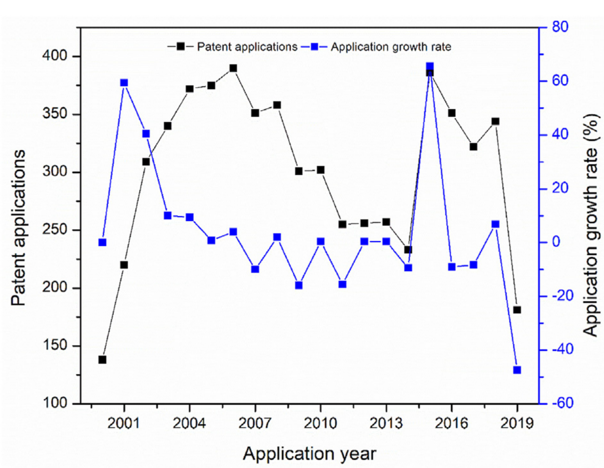

Fig. 3 — Annual patent applications for hydrogen production technologies.

been concentrated in the first half of the study period compared to the second half. Furthermore, 2015 was one of the major years (2nd for patents filed) for hydrogen production development in the field in the last two decades. However, the growth trend with respect to innovators, assignees, and countries/regions shows that the field's growth in 2015 was distributed among only a few innovators/assignees/countries/regions. It is also worth noting that, because it takes around 18–20 months from patent application to publication [61], the number of patents/innovators/assignees/countries decreased significantly in 2019. The results show a fairly consistent trend between the number of annual patents deposited and that of the innovators/assignees/countries/regions involved. The emergence of carbon-neutral/clean energy targets, policies, and stringent emissions standards could ensure more consistent and steady growth in the near distant future.

Data reveals that on 12th January 2000, one of the first patent applications within the study period was made. This patent (Patent No. JP2000233904-A) is on "Apparatus for carrying out catalytic endothermic reactions comprises a thin porous vertical catalyst layer, a channel for oxidant and a channel for collecting the final product". This patent is for the reforming or partial oxidation of methanol and subsequent CO oxidation, especially for producing hydrogen in vehicles [85]. This patent was later published on 29th August 2000. Similarly, one of the most recent patent applications was made on the 23rd of October 2019, and published on the 26th of January 2021. This patent (Patent No. CN110635510-B) is titled "Non-grid-connected wind power system for producing hydrogen by electrolyzing water, has control unit that is respectively connected to wind turbine, quasi-Z source converter, branch switch and power switch," and it serves the purpose of a non-grid-connected wind power system for producing hydrogen by electrolyzing water [86]. This observation signifies the prospect of a growing share of hydrogen production from renewables in the near foreseeable future.

The geographical distribution of the most dominant patenting countries/regions in the field is shown in Fig. 5.

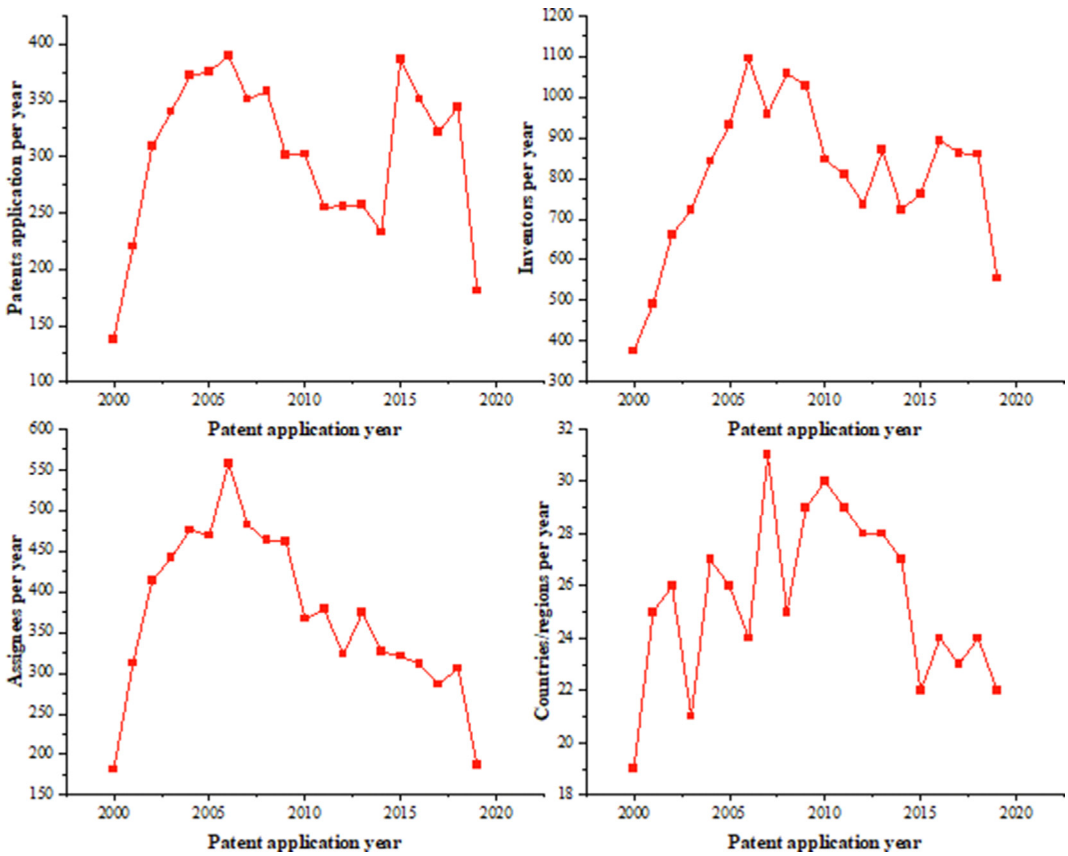

Fig. 4 – Number of patent applications per year compared to that of innovators/assignees/countries/regions.

Japan has led the way in terms of patent applications in the field in the last two decades with 2829 patent applications for hydrogen production technologies. Also featured in the list of the top ten countries or regions are three other Asian countries, i.e., China (1,869), South Korea (709), and India (288). Closely following Japan is the US, with 2032 patent applications. Our top three countries on hydrogen production patents are consistent with the findings of a recent study on research publications on hydrogen production that has also reported that the top three countries with the most contributions to hydrogen production papers are China, the USA, and Japan [87]. Besides, 1060 and 1511 patents were applied

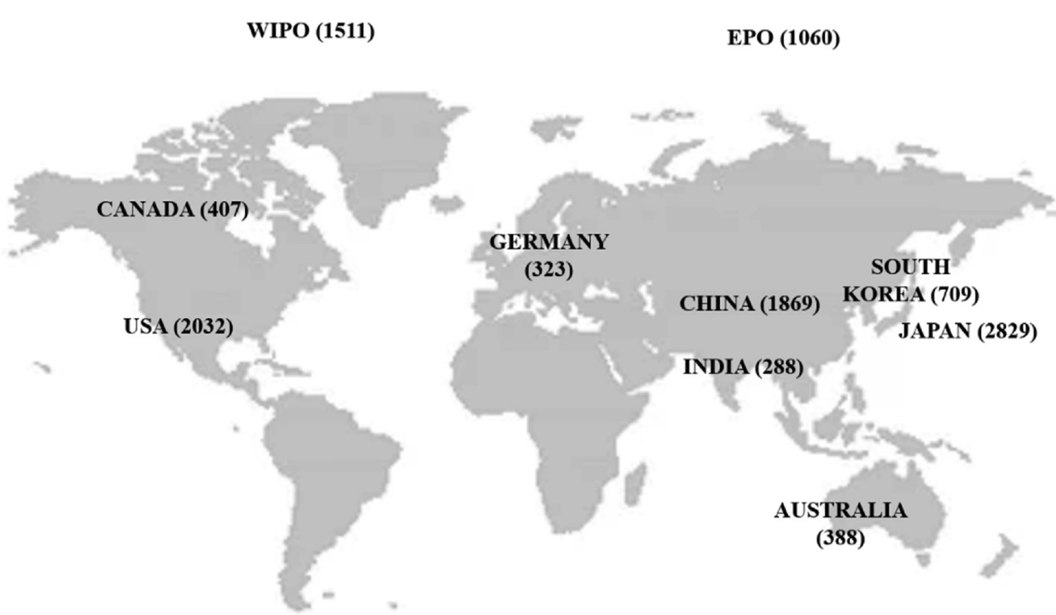

Fig. 5 – Total patent application of top patenting countries/organizations.

through European Patent Office (EPO) and World Intellectual Property Organization (WIPO), respectively. In Europe, Germany takes the helm of affairs ranking 1st in its region and 8th worldwide. Patent activities have not been recorded so far in Africa and large parts of South America. With a majority of these regions/countries classified as low- or mid-income level, it is obvious that the main setback for the lack of contribution to the field has to do with no or low budget allocation for the development of clean fuels such as hydrogen [88]. Furthermore, the existence of clear and active policies on the future adoption of hydrogen fuel influences the patent activities across nations. For instance, in 2017, Japan became one of the first countries to announce a basic hydrogen strategy, and it has since detailed plans to transform into a hydrogen society. The approach aims to attain cost parity with competitive fuels for power generation, such as liquefied natural gas. It has also established realistic cost and efficiency objectives for each application, aiming for electrolyzer costs of $475/kW by 2030, an efficiency of 70%, and a hydrogen production cost of $3.30/kg. The Low Carbon Fuel Standard was revised in California (US) to mandate a stricter decrease in carbon intensity by 2030, incentivize the establishment of refueling stations, and allow CCUS operators to participate in earning credits from low carbon hydrogen. By 2030, the California Fuel Cell Partnership has set a goal of 1000 hydrogen refueling stations [17]. In 2020, a hydrogen strategy was adopted by a number of EU nations, including Germany, France, Italy, and Spain. In the scope of the Next Generation EU, they also committed roughly €11.5 billion to hydrogen fuel development from 2021 to 2026, including €3 billion in Germany, €3 billion in Italy, €2 billion in France, €1.5 billion in Spain, and around €1 billion each in Poland and Romania [89].

Patenting activities vary with time from one jurisdiction to another. Given the energy and environmental situations at the time, a country may decide on which technology to invest most of its resources. Hence, in Fig. 6, we compare the patenting activities of the six major countries in the field with respect to time. The study period has been divided into four phases – each phase representing five years. It can be observed that the trend in patent applications amongst these six countries varies. Japan, for instance, was an active country between 2000 and 2009, amassing 1984 patents within this period. However, from 2010 to 2019, Japan only filed 845 patents which is less than half their activities in the first decade. With the exception of China, the rest of the four countries followed a similar pattern as that of Japan. In fact, China's effort during the last ten years has increased almost three folds relative to their activities between 2000 and 2009. Japan, the US, South Korea, and Canada have all recorded their most active periods between 2005 and 2009; whiles Australia is the only country to have its most active patenting period between 2000 and 2004. It is clear from these statistics that there was much interest in developing the field within the first decade (2000–2009) compared to the last ten years.

International patent collaboration can have a favorable impact on the growth of a technological field. Kerr and Kerr [90], for example, looked at the quality of patented research projects. They discovered that patents created collaboratively by global research teams produce better discoveries than patents developed entirely by local scientists (i.e., only in the firm's home country). Patent collaboration or sharing across countries/regions/organizations, collectively in the field of hydrogen production, is depicted in Fig. 7. Each node in this network represents a jurisdiction. A connection between two nodes indicates that they are co-owners of a patent or that they jointly applied for one, indicating technical collaboration. The goal of measuring and analyzing the patent cooperation network is to identify significant technology holders in the field of hydrogen production and to investigate the cooperative relationships between core jurisdictions. The node size demonstrates

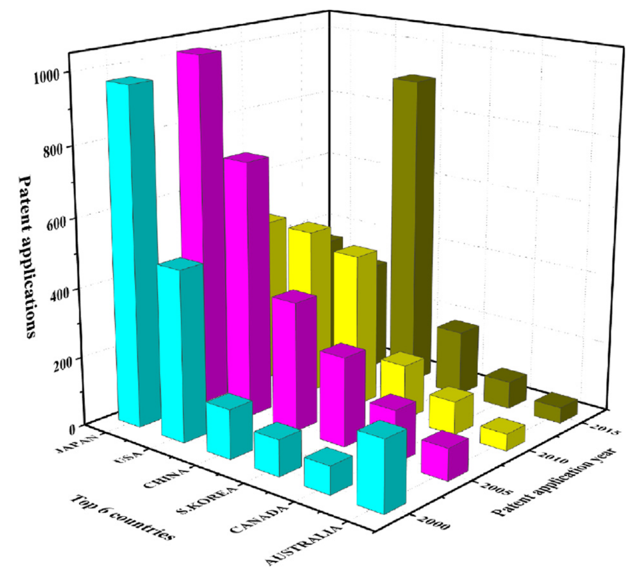

Fig. 6 – Patenting activities of six major countries from 2000 to 2019.

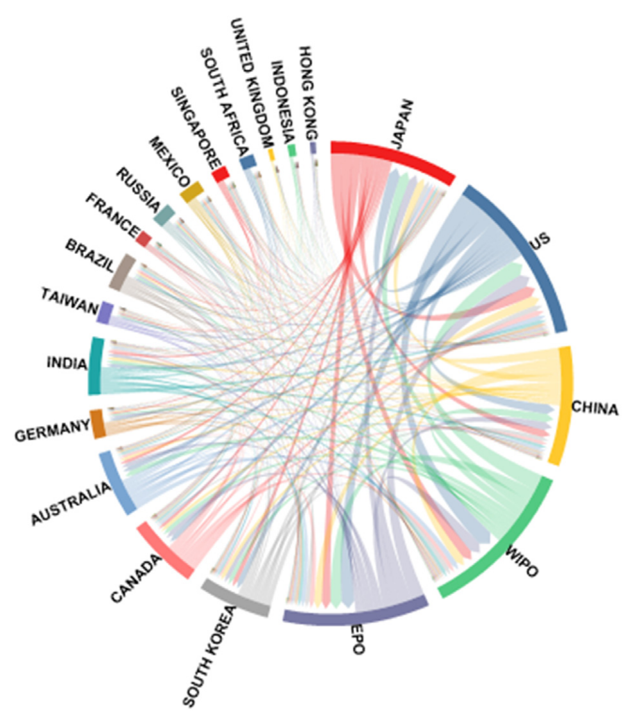

Fig. 7 – International patent collaboration among top 20 jurisdictions.

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jurisdictional dominance in information sharing with other jurisdictions. The thickness of the links represents the degree of patent sharing between any two jurisdictions. Per their node sizes, the US shares the highest number of patents with other jurisdictions, followed by WIPO, EPO, and Japan in that order. The highest number of shared patents between any two countries exists between Japan and USA, with 793 shared patents. One such relevant innovation shared by these two countries is "Efficient hydrogen production method, by culturing microorganism with formate dehydrogenase gene under aerobic conditions, culturing obtained cells under anaerobic conditions in the presence of formic acid, using cells for evolving hydrogen". This innovation is useful for hydrogen generation using microorganisms; the hydrogen generated by this method is useful as a fuel for fuel cells [91].

Patent assignees and target markets

Table 2 presents the top 10 most active patent assignees in the field of hydrogen production technologies. Data shows that all ten assignees are Japanese companies, further emphasizing the dominance of Japan in the development of the field. Ranked in the first position with the most deposited patents from 2000 to 2019 is the Panasonic Corporation, with 258 patent applications. During the study period, this company filed one of the most recent patents relating to a "optical semiconductor, a manufacturing method for the optical semiconductor, an optical semiconductor device, a photocatalyst, a hydrogen generation device including the photocatalyst, and an energy system including the hydrogen generation device" (Patent No. JP5165155-B2) [92]. Furthermore, Panasonic introduced the ENE-FARM, the world's first domestic fuel cell cogeneration system, in 2009, which produces power using hydrogen derived from natural gas [93]. At the same time, Panasonic has been researching and developing pure hydrogen fuel cell generators, which use hydrogen directly supplied from the outside to produce power, anticipating the hydrogen society's emergence. Beginning in 2012 at Yume Solar Kan Yamanashi, a facility promoting renewable energy in Kofu City, the Panasonic corporation performed field experiments using similar generators in several locations around Japan. Panasonic Corporation launched a 5-kW pure hydrogen fuel cell generator on October 21, 2021, which creates power through a chemical reaction using high-purity hydrogen and oxygen in the air. Consequently, it is feasible to convert hydrogen to electricity effectively, allowing the product to reach a high electrical efficiency of 56% [93].

The non-Japanese company with the highest number of patent applications is also an Asian company from China, Shanghai Hejide Dynamic Hydrogen Machine Co. Ltd, with 63 patent applications – ranking 12th in the field. Also, the non-Asian company with the most deposited patents from 2000 to 2019 is a US-based company, Intelligent Energy Inc – with 31 patents filed and ranks 24th in the field. Finally, the academic institution with the most contributions to the field is the South China University of Technology (SCUT), with patent applications of 24 and ranks 39th in the field. Since SCUT is the only academic institution featuring in the top 40 assignees with hydrogen production technology patents, we briefly highlight one of their most recent innovations (Patent No. CN109081308-A) on the subject. The innovation is titled "A method of by glycerol and methane co-producing hydrogen and synthesis gas". It discloses a kind of methods by glycerol and methane co-producing hydrogen and synthesis gas, and the innovation can produce purity up to 97% hydrogen [94].

The target market of the top six assignees outside of their home country (Japan) is explored using correlation analysis, as illustrated in Fig. 8. The results show that the US is the world's largest target market for these companies/institutions because it's an innovative and stable market with the largest economy. The results do not come as a surprise because evidence from several financial indexes and reports shows the US as the most attractive market worldwide: (1) In 2020, the US ranked first in the Global Foreign Direct Investment Country Attractiveness with an index value of 75.9 [95]; (2) Similarly, according to the 2018 Global Entrepreneurship Index rankings, US had the highest index (83.6) [96]; (3) The World Bank statistics on foreign direct investment (2019 inflows) [97] shows that the US is the largest recipient (~USD 302 billion) of foreign investment ahead of an economic superpower like China (~USD 187 billion). The aforementioned statistics explain why companies developing hydrogen production technologies target the United States as their primary market.

As discussed earlier, one of the existing gaps in the available literature on the hydrogen energy-related patent analysis is the lack of up-to-date findings on the annual output of patent activities, key innovators, assignees, and their country of origin. The results presented in Technology output and geographical distribution to Patent assignees and target markets contribute to the existing studies by revealing the trend in these aspects of hydrogen production technologies.

Table 2 – Top 10 assignees of hydrogen production technologies.

Rank	Assignee	Patents deposited	Country
1	Panasonic Corporation	258	Japan
2	JX Nippon Oil & Gas Exploration	187	Japan
3	Toyota Jidosha	130	Japan
4	Panasonic Intellectual Property Management	95	Japan
5	Nissan Motor Co Ltd	92	Japan
6	Toshiba KK	89	Japan
7	Tokyo Gas Co Ltd	82	Japan
8	Honda Motor Co Ltd	75	Japan
9	Toyota Chuo Kenkyusho	69	Japan
10	Mitsubhishi Jukogyo	68	Japan

Areas of technological development

Derwent Manual Codes (DMC) can be used to examine the technological categories involved in hydrogen production technologies (as illustrated in Fig. 9) to better understand the core areas of development in the field. This categorization identifies the innovation's new technical characteristics or significant features, such as technical features and claim applications. This classification follows the same hierarchical structure as the IPC, although with fewer details. Each patent application in the DII is given at least one Derwent class based

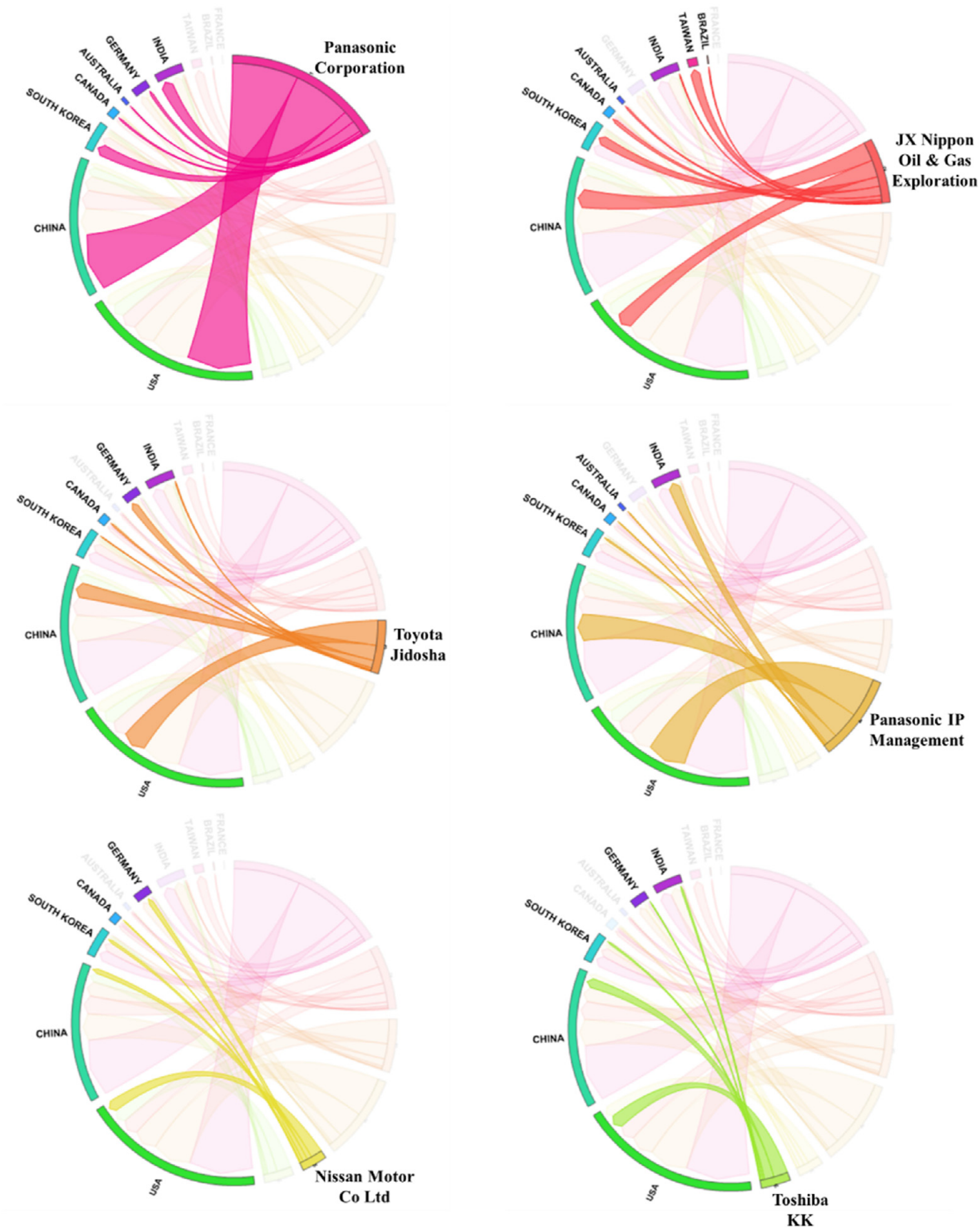

Fig. 8 – Top 6 assignees' major target markets outside home country (note: if the assignee has no patent relationship with a particular country, the node is deactivated).

on the linked technical field, which includes one capital letter and two-digit code. DMCs are more up-to-date and thorough than IPCs to some extent [98]. The co-occurrence of DMCs is due to the fact that a single patent can be categorized into multiple DMCs. From the network analysis, it is fair to say that the technology category that has the most co-occurrence (per link strength) with other technological categories in a single patent has been the most focus of the numerous innovators in the field. For specificity, DMCs belonging to the same family are analyzed independently throughout the analysis. Thus, the key focus of the field, according to the largest cluster (red), is seen in E31-A02C. This E31-A02C has a total link strength of 16,168 and appears in 2291 patent applications. In the second-largest community (green), the focus of the field is reflected mostly by the technology category X16-C17A, with a total link strength of 16,182 and 2279 patents that features this category of technology. Finally, the technology category H06-A03, with a link strength of 10,028 and occurring in 1312 deposited patents, represents the focus of the smallest community in the network. It is also worth noting that the two categories of innovation with the most co-occurrence are L03-E04I and X16-C17A – these two technology categories have co-occurred in 1413 patent documents. Table 3 provides a description of the top 10 technology categories in the field of hydrogen production. Details of other DMCs not listed in Table 3 can be found at https://clarivate.com/derwent/dwpi-reference-center/mcl/ and https://clarivate.com/derwent/dwpi-reference-center/dwpi-manual-code/.

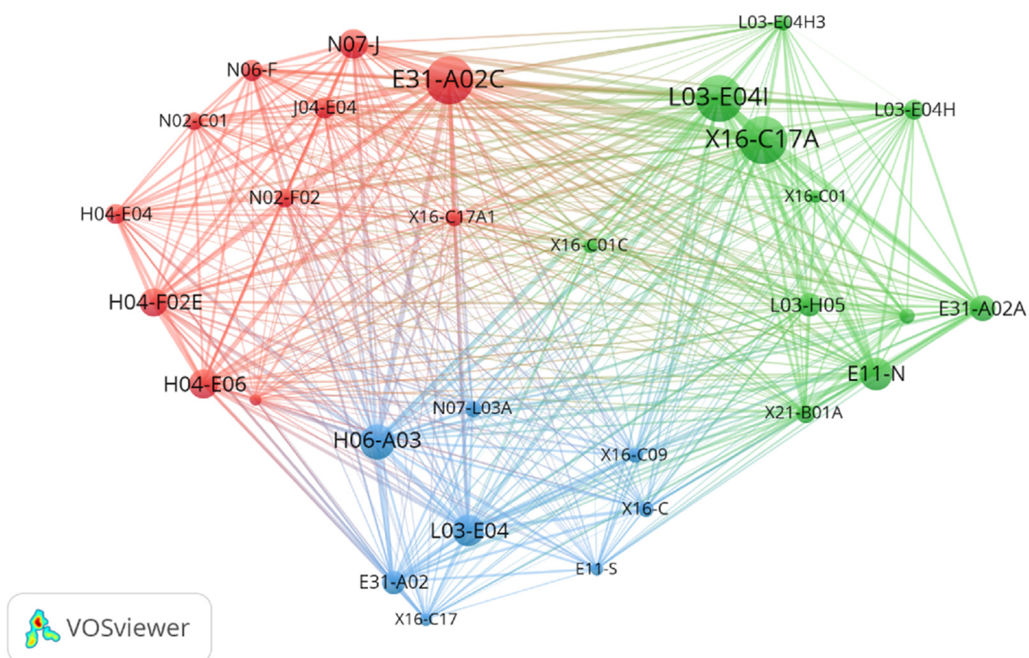

Fig. 9 – Co-occurrence network of core technological categories.

Results show that the technological innovations in the field relatively focus more on methane/methanol steam reforming, electrical means of producing hydrogen, and hydrogen production for use in fuel cells. To conclude this section, Fig. 10 depicts a density visualization map. Density visualization maps can be used to identify and discriminate between potential technologies. Density visualization maps can detect well-developed technologies and, at the same time, reveal those with future prospects. According to these maps, locations with a relatively low density on the patent map are identified as prospective research gaps that have not yet been completely investigated but have great potential for further development. From the figure, the ten most important but relatively ignored technological areas/direction are E31-N05C (carbon dioxide), X16-C17 (fuel processing), E11-S (storage), X16-C01 (solid oxide and solid polymer fuel cell), X16-C (fuel cells and associated components), X21-A01J (fuel cell vehicle), L03-E04H3 (production of other fuel cell components), X16-C09 (control - Includes catalyst temperature control using fuel and air flow; gas and air circulation, etc.), N07-L03A (batteries, fuels cells), and N02-C01 (Nickel element catalyst). It can be observed that most of these relatively under-explored areas have a direct link to the production stage of hydrogen, whiles some are related to the aftermath of production, such as storage and consumption. Researchers in the field could make a conscious effort to direct some attention and resources to these ignored areas to further drive the progress of the field.

Recent technology direction of key economies

The dynamism involved with technological changes and focus between the top six patenting countries involved in hydrogen production in the last five years is investigated (Fig. 11). This approach helps to reveal the current direction of the field and what could be expected in the near-distant future. It is clear that there has not been a significant difference in technological focus between these countries. Their focus in the last five years has been primarily on technologies classified under X16-C17A, E31-A02C, and E11-N. Japan, the US, China, and South Korea have had quite similar interests in the last five years,

Table 3 – DMC subclasses of hydrogen production technologies.

Rank	DMC subclass	Technology category	Patent count
1	E31-A02C	Hydrogen production by ‘other’ means (e.g., steam reforming)	2291
2	X16-C17A	Includes all aspects of hydrogen manufacture if for ultimate, stated use in fuel cells	2279
3	L03-E04I	Fuel cells - Hydrogen generation	1869
4	H06-A03	Gaseous fuels - Hydrogen	1312
5	E11-N	Electrochemical, electric discharge - processes, apparatus	1186
6	L03-E04	Fuel cells (general)	1128
7	E31-A02A	Hydrogen production by electrical means	920
8	H04-E06	Other petroleum processes - hydrogen manufacture	918
9	N07-J	Catalyst use in the production of inorganics	820
10	H04-F02E	Preparation/composition of catalysts for other petroleum processes	793

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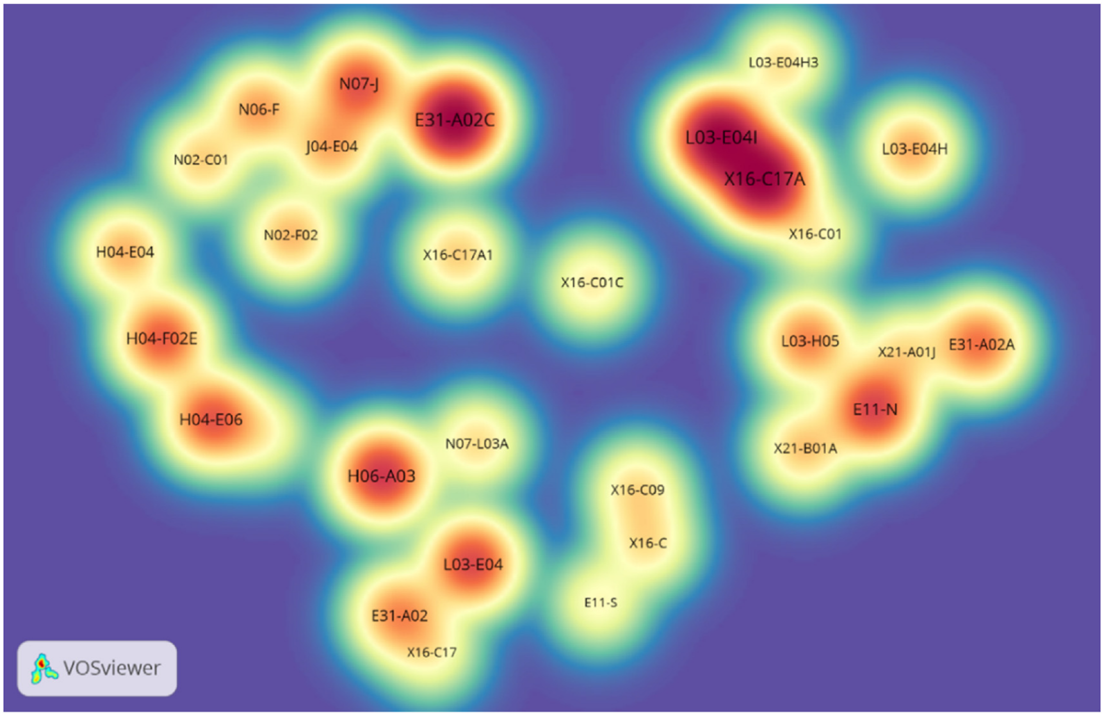

Fig. 10 – Developed and ignored technological areas.

whiles the focus of Canada and Australia appears to be somewhat divergent from the other economies. However, few important and unique classes of technologies have emerged in the last five years – W06-C01C in South Korea; E31-A02A in South Korea and Australia; N07-J in Canada and Australia; H09-F03 and E10-J02D1 in Canada; E31-N05C, E11-W, and E31-A01 in Australia. W06-C01C are technologies classified as electrical equipment; for instance, W06-C01C3 relates to electrical power generation and distribution. E31-A02A represents technologies for producing hydrogen by an electrical method. In the context of the current review, N07-J is dedicated to catalysts used for hydrogen production. Fuels produced from municipal and agricultural waste treatment are classified under H09-F03. Hydrogen production via municipal solid waste, agricultural waste, and forest residue gasification is one of the promising and economic technologies [99]. These wastes can broadly be categorized as waste-activated sludge, algae biomass, and cellulose-based

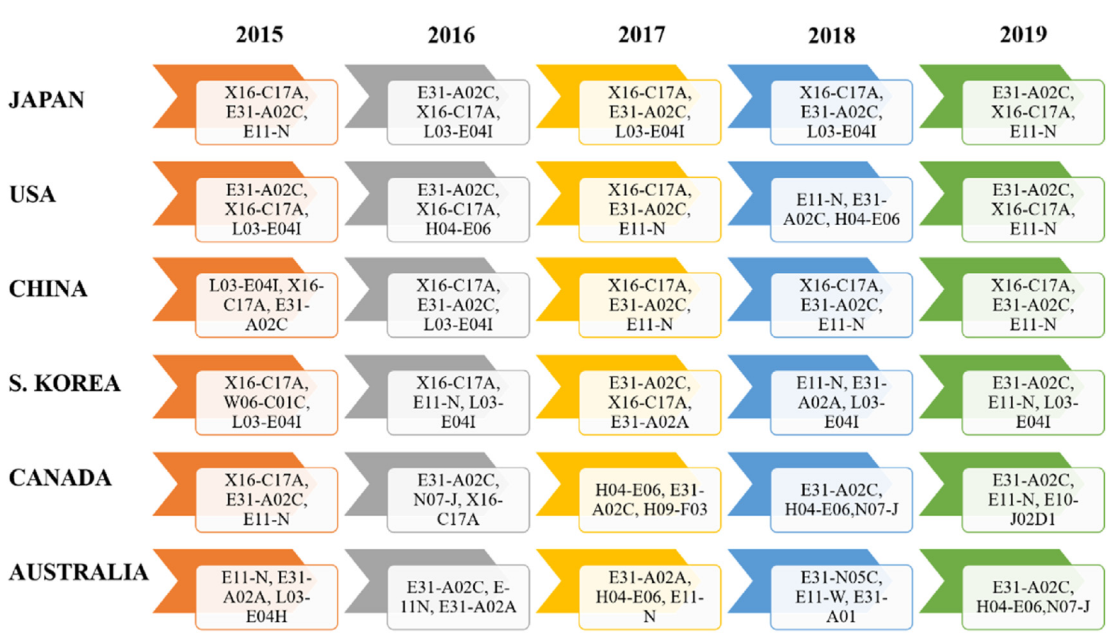

Fig. 11 – Technological focus of top patenting countries in the last five years (2015–2019).

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biomass [100]. Hydrogen production using these feedstocks supplies dual benefits of energy generation and waste treatment since agricultural and municipal wastes can be deposed at the same time [100]. E10-J02D1 is for methane: the steam methane reforming process produces almost 95% of the world's hydrogen. Natural gas is reacted with steam at a high temperature to form carbon monoxide and hydrogen in this process [101]. Additional steam combines with the carbon monoxide in a later process, i.e., the water gas shift reaction to create more hydrogen and carbon dioxide. E31-N05C relates to CO_2 and includes carbonic acid: technologies involved in removing or separating CO_2 during the production of hydrogen are likely to be assigned under this technology class. For example, Patent No. GB2466554-A; WO2010073026-A1; GB2466554-B; HK1142358-A1 describes such innovations. The innovation is titled “Manufacturing town gas from landfill gas, comprises recovering landfill gas, removing contaminants and water, adjusting carbon dioxide level to give stream comprising carbon dioxide and methane and mixing hydrogen containing gas stream”. The advantage of this technology is that it employs cryogenic capture units, which are operated at temperatures and pressures that efficiently separate some of the carbon dioxide contained in landfill gas, decreasing the load on the hydrogen producing equipment [102]. E11-W describes environmentally friendly innovations – an example of such environmentally friendly innovations in this category is seen in the works (Patent No. JP2016222781-A; JP6570111-B2) of innovators Kano J and Toka S of the Tohuku University. Their innovation is titled “Producing hydrogen used for producing hydrogen gas used as an energy source as a fuel of internal combustion engines, by mixing calcium hydroxide and nickel hydroxide in cellulose or sewage sludge as biomass resources, and heating mixture”. The method is environmentally-friendly, suppresses warming, strongly exhibits low carbon society assembly, produces highly pure hydrogen, and ensures a stable supply of energy [103]. Finally, some innovations in the area involve either the simultaneous production of hydrogen and CO or producing hydrogen whiles limiting the production of CO. These types of innovations are likely to be classified as E31-A01 (hydrogen + carbon monoxide). Two of such innovations are reviewed hereafter. Patent No. EP1077198-A2 titled “Catalytic steam reforming of hydrocarbon feedstock for producing hydrogen and/or carbon monoxide rich gas, involves catalytic pre-reforming feedstock followed by steam reforming” - the innovation's use is for producing hydrogen and/or carbon monoxide rich gas [104]. On the other hand, Patent No. JP2005082436-A titled “Hydrogen production apparatus has modification portion having modification catalyst, and carbon monoxide decreasing portion having carbon monoxide decreasing catalyst and sulfur compound removal agent” - This hydrogen generating device has enhanced carbon monoxide reduction capabilities. The use of a noble metal catalyst prevents the poisoning of the catalyst by sulfur compounds and the lowering of catalytic properties [105].

Research thematic areas

Based on the technology focus of the 6041 patent documents retrieved, text mining was performed with ITGInsight to extract the relevant terminologies involved in hydrogen production. The top 150 terminologies were used to construct a cluster (Fig. 12) to group and summarize these innovations according to their main thematic direction. Cluster analysis has also been used in patent analysis to group patent data based on its relevance [62]. As a result, three main thematic directions were discovered. These themes can be directly related to hydrogen production or the aftermath use or effect of the hydrogen production process.

The largest cluster in the network (red) involves terms related to hydrogen production by electrical means for fuel cell use – and it can be speculated that, for the last twenty years, the development in the field of hydrogen production has been in this area. Hydrogen fuel cells emit no harmful pollutants and eliminate the expenses involved in handling and storing hazardous chemicals such as battery acid or diesel fuel [106]. In fact, when powered by pure hydrogen, the only byproducts are heat and water, making hydrogen a zero-emission, sustainable source of energy. Many well-planned corporate sustainability programs use hydrogen fuel cells. According to the US Department of Energy [107], hydrogen fuel cells typically exceed 60% energy efficiency. This range is comparable to a normal internal combustion engine in a vehicle, which is about 25% energy efficient [106]. The word ‘electric vehicle’ is also evident in this red community. Hydrogen Fuel Cell Vehicles (FCVs) are a branch of electric vehicles (EVs) in the sense that hydrogen gas from the vehicle's fuel tank combines with oxygen (O_2) from the surrounding air to produce electricity, with only water and heat as byproducts. In the last five years, two such innovations in this community (red) are herein summarized: Patent No. US9537167-B2 titled “Fuel cell for generating hydrogen gas, electrical power, and mediation of electrochemical reactions and reactant transport, comprises electrolyte membranes disposed between anode and cathode, where an electrode is disposed between membranes”. This innovation's advantage is that the fuel cell uses hydrogen to generate electricity from an alcohol fuel and provides increased power output [108]. Patent No. KR2017015822-A titled “Fuel cell system for use in, e.g., diesel engine vessel has hydrogen generation part for producing fuel, and control unit for controlling extraordinariness for supply part in order to supply fuel to fuel anode of cell in emergency occurrence”. The system reduces the management cost and fuel wastage rate according to the excessiveness production of fuel [109].

The second-largest community (green) relates to hydrogen production via reforming methods – methane/methanol steam reforming is all classified under this cluster. Steam reforming, also known as steam methane reforming, is a technique of creating syngas (hydrogen and carbon monoxide) by the reaction of hydrocarbons with water. Natural gas is commonly used as a feedstock. The primary goal of this technique is to produce hydrogen. When waste carbon dioxide is discharged into the environment, hydrogen created by steam reforming is referred to as ‘grey hydrogen,’ whereas ‘blue hydrogen,’ when the carbon dioxide is (mainly) absorbed and stored geologically. On the other hand, methanol reformer (methanol steam reforming) is a device used in chemical engineering, particularly in fuel cell technology, that may create pure hydrogen gas and carbon dioxide by reacting

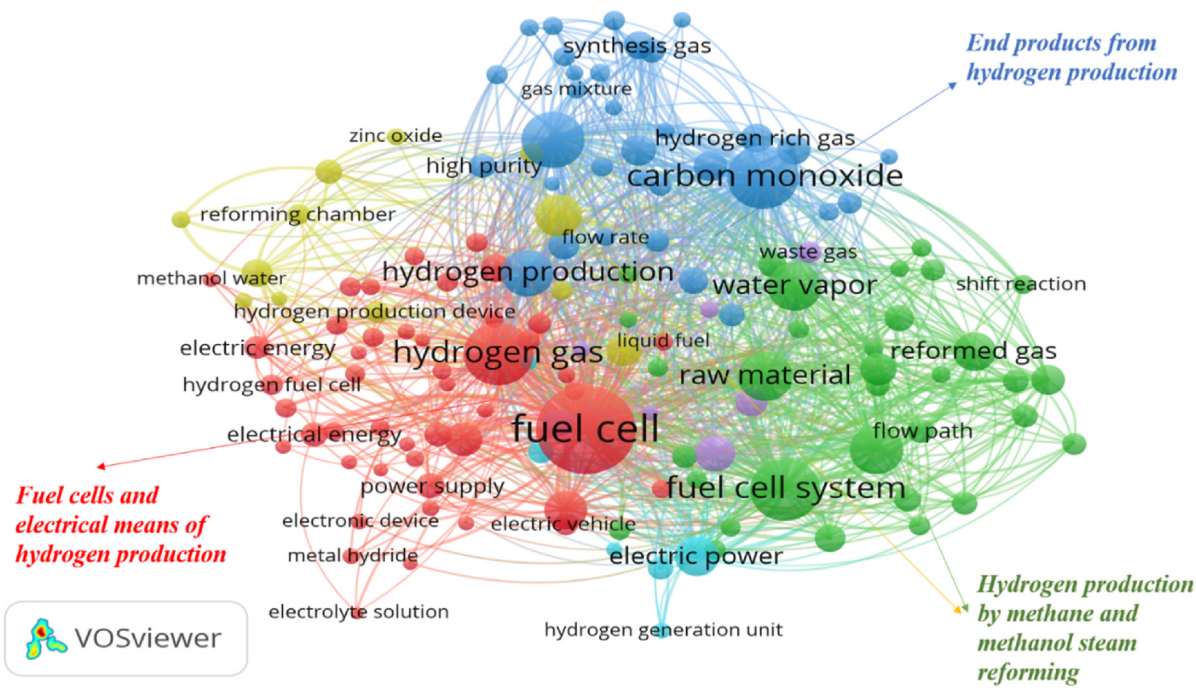

Fig. 12 – Cluster analysis of research thematic areas.

a methanol and water (steam) mixture. It is worth mentioning that while hydrogen energy use produces no CO_2, a methanol reformer, just like methane reforming, produces the gas as a byproduct. However, methanol (made from natural gas) utilized in an efficient fuel cell emits less CO_2 into the environment than gasoline [110]. Methane steam reforming typically requires temperatures of up to 900 °C to achieve high equilibrium yields [111]. On the other hand, higher-temperature operations need additional insulation and thermal integration. Liquid fuels such as alcohols are potential possibilities for portable hydrogen production. Liquid fuels such as alcohols are potential possibilities for portable hydrogen production. Methanol, in particular, is an attractive fuel due to its high energy density, high hydrogen-carbon ratio, and ready availability [112]. Furthermore, methanol offers the benefits of being sulfur-free and ultra-clean [113–115]. More specifically, the steam reforming of methanol takes place at substantially lower temperatures, typically within 250–300 °C. Furthermore, low operating temperatures can minimize heat losses and reduce the undesired carbon monoxide [112], thereby offering a significant advantage over hydrocarbon steam reforming [116]. Chen et al. [111] made comparisons between methane and methanol steam reforming in thermally integrated microchannel reactors for hydrogen production through a computational fluid dynamics study. Steam reforming of both fuels was demonstrated to be feasible in millisecond reactors under a variety of conditions, although extremely careful design is required. Methanol reforming had the potential to be more efficient, providing a better solution not just for simplifying design but also for increasing power and efficiency.

In the third and final community (blue), terms related to the main/by-products from the hydrogen production process are found. This includes hydrogen gas with a focus on its richness and purity. Also, the goal of converting/eliminating/reducing pollutants such as CO and CO_2 during the production of hydrogen is represented in this community. We already discussed the release of such pollutants from steam reforming processes; however, coal gasification is another source of carbon emissions during the production of hydrogen. Coal gasification is a process that employs steam and oxygen to break molecular bonds in coal and produce a gaseous mixture of hydrogen and carbon monoxide. Some innovations made in recent years belonging to this blue community had the goal of producing rich hydrogen of high purity and, in the process, reducing pollutants. Patent No. US9108894-B1 is one of the latest innovations. This innovation is titled "Using biogenic carbon dioxide derived from non-fossil organic material for fuel production, comprises, e.g., converting biogenic carbon dioxide and hydrogen that is sourced from hydrogen production process to, e.g., biogenic carbon-based fuel". By using non-fossil organic material, the method improves product yield and produces more fuel or fuel intermediate in a cost-effective manner; reduces the life cycle greenhouse gas emissions associated with the biofuel or biofuel intermediate; provides the fuel with improved energy content; avoids the harmful tailpipe emissions of conventional fossil-based fuels; introduces low energy fossil carbon dioxide underground, and thus does not contribute to atmospheric carbon [117].

Feedstock-based comparative trend

Technology life cycle and assessment

The life cycle of two main groups of hydrogen production technologies according to feedstock (i.e., fossil and renewable) is discussed in this section. The life cycle of the technology begins with the introduction, to growth, then maturity, and ends in saturation, where the research on the technology ceases and is expected to decline afterward. From Fig. 13, it is seen that, for fossil-based technologies, the introduction phase ended in 1995. The growth phase occurred between 1995 and 2013. By 2013, the technologies in the field had already reached maturity. By 2031 and 2049, the technologies will reach 90% and 99% saturation levels, respectively. For renewable-based technologies, the introduction phase ended in 2000. The growth phase occurred between 2000 and 2017. By 2017, the technologies in the field had already reached maturity. By 2034 and 2051, the technologies will reach 90% and 99% saturation levels, respectively.

In addition, the technology maturity rate (TMR), number of potential patent applications (PPA), and the expected remaining life (ERL) at a 90% saturation level of the various groups of technologies are analyzed. It was observed that the TMR of fossil-based technologies is about 66% compared to approximately 57% of renewable-based technologies. This implies that relatively, the growth of fossil-based hydrogen production technologies is almost stagnant and has barely little potential for further growth. The renewable-based technologies, on the other hand, have a greater potential for technological development with rapid growth. The PPA of fossil and renewable-based technologies is 1609 and 2758 documents, with an estimated time remaining to reach saturation in 12 and 15 years, respectively.

Trend analysis of technologies

Comparative mapping of the last five years of hydrogen production development based on three different feedstocks is discussed in this section. It is seen from Fig. 14 that in recent years the main focus of development has been on renewable-based technologies, especially water-based hydrogen production options. The trend does not come as a surprise as the share of hydrogen production from renewables, especially water (electrolysis) and biomass, can increase from the current 5%–30% by 2050 [25,118]. According to IEA [21], global hydrogen demand by production technology in the Net Zero Scenario 2020–2030 could see hydrogen production via electrolysis reach 79.72 Mt by 2030 compared to 55.56 Mt (fossil with CCS), 13.43 Mt (fossil with CCU), 52.78 Mt (fossil), and 10.67 Mt (by-product in refineries). Currently, steam methane reforming and coal gasification have the lowest hydrogen production costs (1 \$/kg H_2), owing to huge existing structures with a technology readiness level (TRL) of 9 and low feedstock prices. However, biomass prices are projected to decline by 2050 at the expense of fossil resources. Biomass gasification and pyrolysis are similar to methods that use fossil fuel. In the following two decades, they are predicted to grow to a TRL of up to 9 [119]. Furthermore, a significant increase in renewable electricity production and a growing emphasis on the environmental footprint of traditional production methods have pushed innovators to develop efficient solutions with significantly lower levels of environmental impact. Hydrogen production via fossil fuels is the most economical and mature but at the expense of serious environmental problems. Biomass gasification provides an alternate solution because of its low cost and lack of additional carbon emissions [2]. In the long term, renewable-powered water electrolysis (e.g., wind or solar) at central or semi-central facilities could also be an eco-friendly alternative [29]. On the other hand, when compared to steam methane reforming (without carbon capture), the cost of electrolytic hydrogen is 6–27% higher. However, this

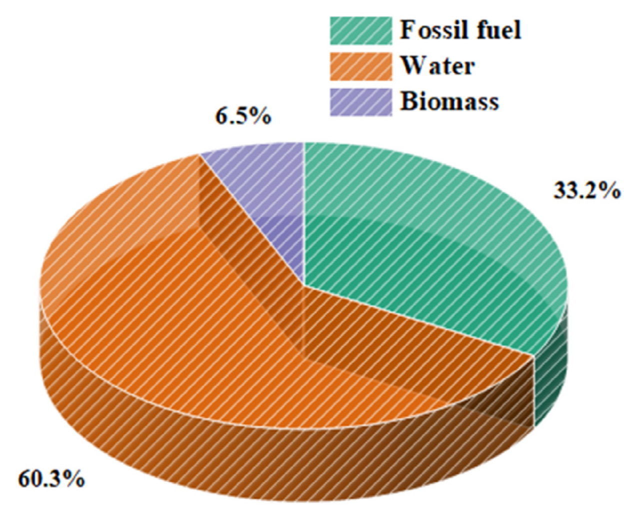

Fig. 14 – Share of hydrogen production patents according to feedstock in the last five years.

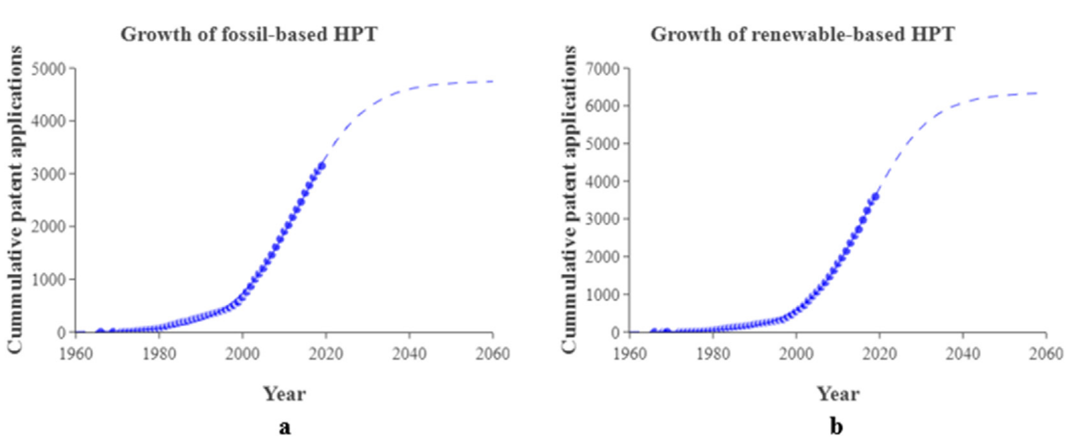

Fig. 13 – Technology life cycle of hydrogen production (a – fossil-based technologies; b – renewable-based technologies); forecasted fit as dashed lines; HPT-hydrogen production technologies.

cost becomes comparable to steam methane reforming once carbon capture and storage are included in the analysis [120]. Therefore, it makes sense that, in the context of a future low carbon society, major innovators in the field have recently paid much attention to renewable energy-based technologies for hydrogen production. The result above is consistent with a patent analysis conducted by IRENA, which has revealed that since 2016, the number of patent families for water electrolysis technologies surpassed the number of patents related to producing hydrogen from fossil sources (e.g., solid or liquid coal and oil-based hydrogen sources) [121].

It is also worth noting that in the last five years, steam reforming, electrolysis, and biomass pyrolysis remain the main patent-deposited technologies under fossil, water, and biomass-based technologies, respectively (Fig. 15).

Patent distribution among key countries and assignees. In Fig. 16, the main patenting countries for the three groups of technologies are displayed. It can be seen that, in the last five years, China has been the most active patenting country in both fossil and renewable-based technologies. This is consistent with our earlier results in Technology output and geographical distribution, Fig. 6, which revealed that China, since 2015, has become the most dominant country in the field, ahead of Japan and the US. Hydrogen is not a novel concept in China. It is by far the world's greatest hydrogen producer, generating 22 million tons of hydrogen per year, accounting for one-third of global output [122]. China's hydrogen energy industry is booming due to massive investment over the last five years, as the government strives to attain carbon neutrality by 2060 and peak emissions by 2030. China has increased its investments in hydrogen; the country's national and local governments have included the hydrogen industry as one of China's six future industries in the 14th Five-Year Plan (2021–2025) [123]. China's hydrogen gas demand for 2025, 2030, and 2050 are estimated at 35.5 million, 37.15, and 97 million metric tons, respectively [124]. The China Hydrogen Alliance, a government-supported industry group, predicts that by 2025 the output value of the country's hydrogen energy industry will reach 1 trillion yuan ($152.6 billion), and by 2030 that China's demand for hydrogen will reach 35 million tons, accounting for at least 5% of China's energy system [123]. The country hopes that hydrogen will account for 10% of the Chinese energy system by 2040 [122]. Closely following China in all three groups of technologies is the US. Furthermore, countries like Japan, South Korea, and Canada are among the top ten active countries in the field irrespective of the technology. However, for countries such as India, Germany, and Australia, their dominance is witnessed in water-and-fossil-based technologies, losing their spot to Argentina, Russia, and Poland with respect to biomass-based technologies.

In Fig. 17, the main assignees under each group of technology are presented. Under fossil-based technologies, the most productive assignees are Sinopec, Haldor Topsøe, and Air Liquide SA. Using water as feedstock for hydrogen production, Toshiba KK, Haldor Topsøe, and Korea Institute of Energy Research are the leading technology developers in the last five years. The top assignees in this category are very much distributed across multiple countries. It is seen that for biomass-based technologies, the top assignees are mostly Chinese-based companies, universities, or research institutions. The leaders in the production of hydrogen from biomass are Henan Baiyoufu Biological Energy Co Ltd, Sinopec

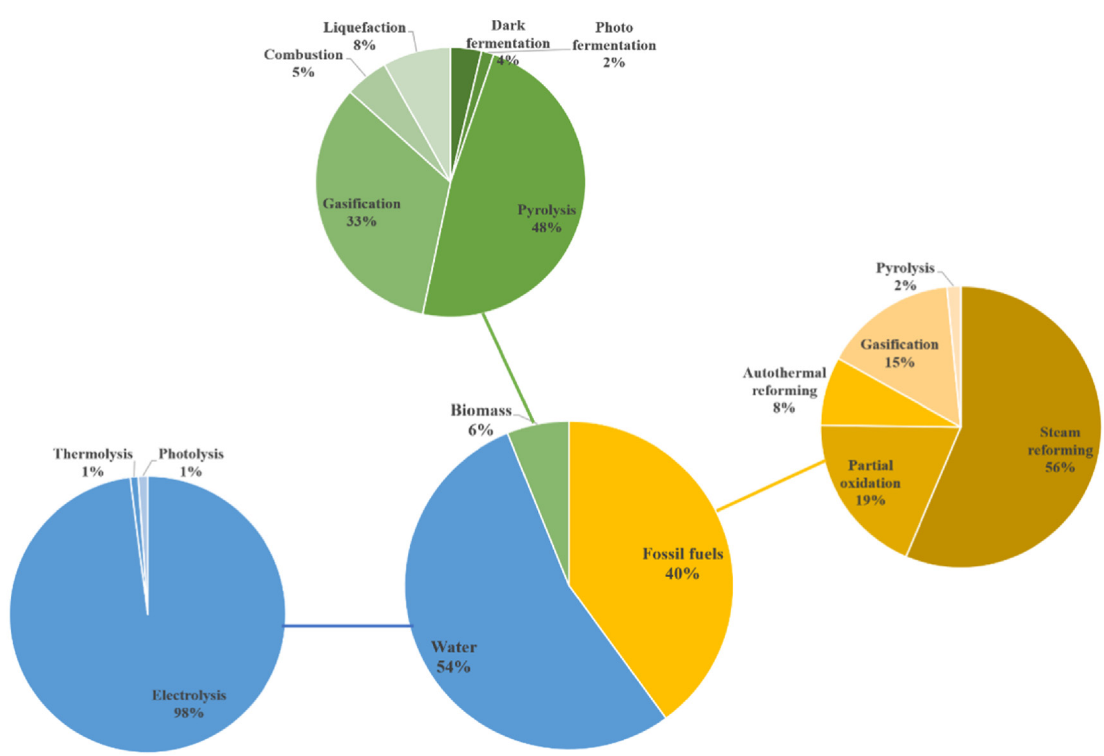

Fig. 15 – Share of patents on specific technologies in the last five years.

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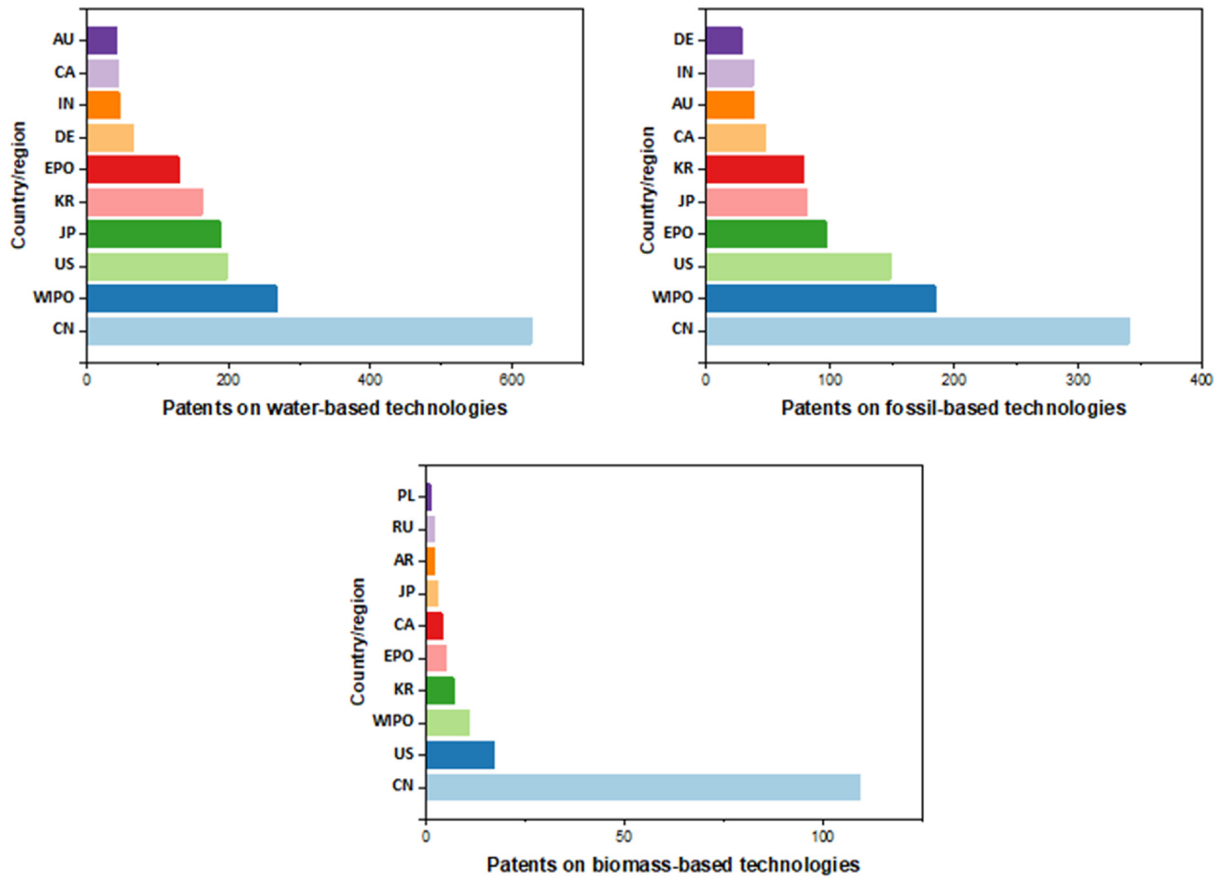

Fig. 16 – Top ten patenting countries/regions/organizations in each technology group in the last five years.

Luoyang Guangzhou Engineering Co Ltd, and Shanghai Huachang Environmental Protection Co Ltd. It is important to note that majority of the patent holders for fossil and water-based technologies are companies; hence the commercialization of these latest developments is in their advanced stages. However, biomass-based technologies are dominated by universities and research institutions; hence the progress to the commercialization of these technologies is relatively immature.

Main technical areas and research hotspots. This section briefly reveals the main areas of development and research hotspots of fossil, water, and biomass-based hydrogen production technologies in the last five years. While at it, some examples of existing patents in the field are reviewed as highlights.

Fossil-based technologies. The main technical areas of development for hydrogen production from fossil fuels is shown in Fig. 18. It is seen that despite its high TRL, steam reforming techniques continue to be a major area of development. It is also seen that innovators in the field have recently paid more attention to catalyst development and use in the production of fossil-based hydrogen.

Catalysts in the chain of hydrogen production from fossil fuels are significantly progressing. Most steam reforming research has recently been on catalyst performance to maximize hydrogen yield by resisting catalyst sintering and limiting the effects of carbon deposition and sulfur poisoning [35]. Catalytic gasification is also mentioned in the literature as a way to increase hydrogen-rich syngas production. When a catalyst is added to the gasification process, it promotes the cracking reaction and lowers the activation energy, thereby lowering energy consumption. There are different types of catalysts used for this purpose, including noble metals, mineral, or alkali metal catalysts, standing out from all is Ni-based catalysts due to their low prices and high activity, which explains why they are widely used for catalytic gasification [125]. Nickel oxide/cerium complex methane steam reforming catalyst useful for hydrogen production is described in Patent no. CN111974402-A. The steam reforming catalyst uses raw material steam directly to pretreat and activate the catalyst, increasing the activity and stability of methane steam reforming. The approach is simple, low-cost, and decreases the risk of the process and process flow, as well as energy consumption and costs for methane steam reforming and conversion, and it boosts the efficiency of methane steam reforming to yield hydrogen [126]. Brazilian patent BR102017001330-A2 describes a catalyst for producing hydrogen from steam reforming of alcohols or hydrocarbons. The catalyst is distinguished by nickel as the phase, strontium as the promoter, and activated charcoal as the support. The catalyst is used to assist the movement of carbon monoxide with water vapour on the metal surface, and it is more stable and less prone to coke production [127].

The research hotspots in the fossil-based hydrogen production methods in the last five years are represented in Fig. 19. It can be observed that the innovators are focusing on

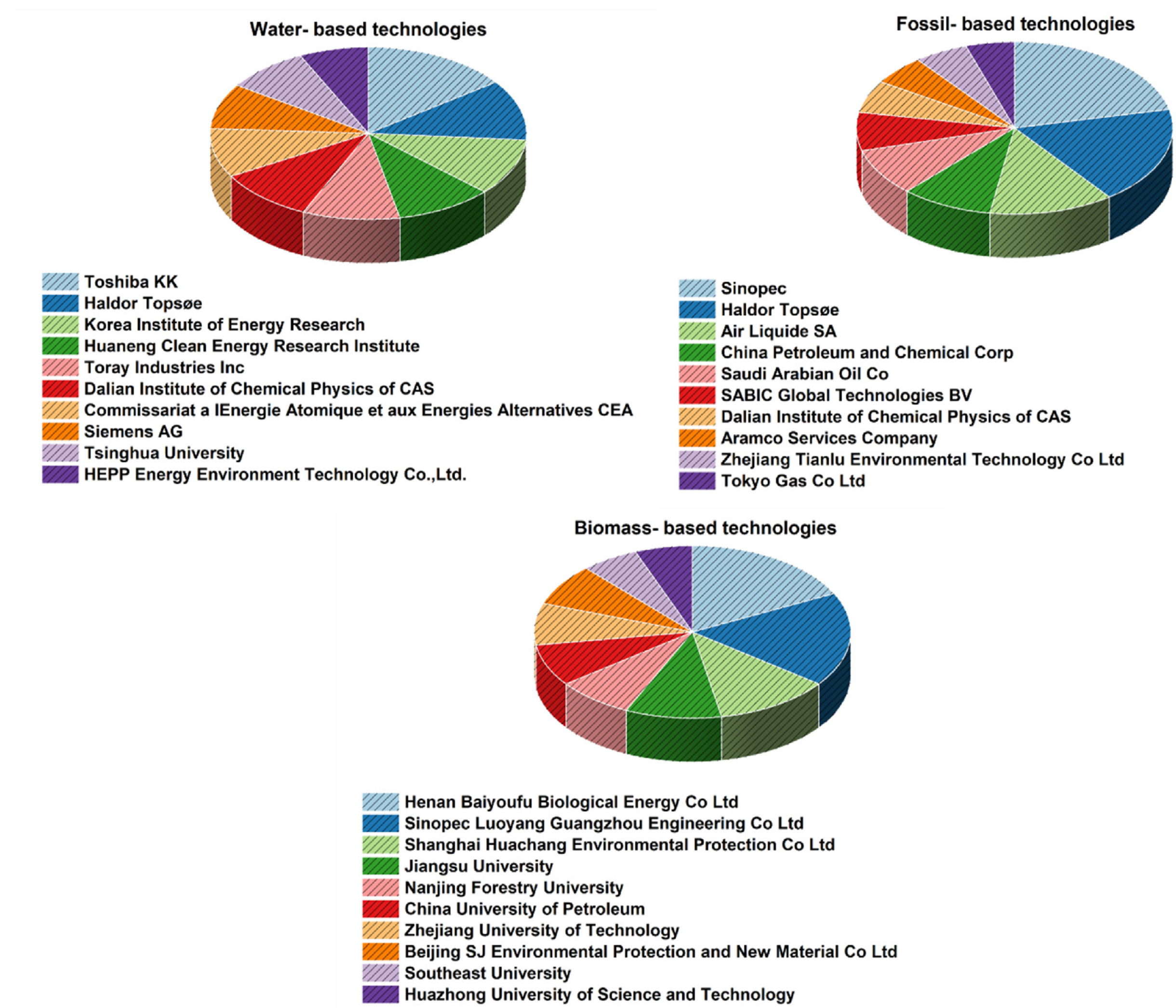

Fig. 17 – Main assignees with respect to technology category in the last five years.

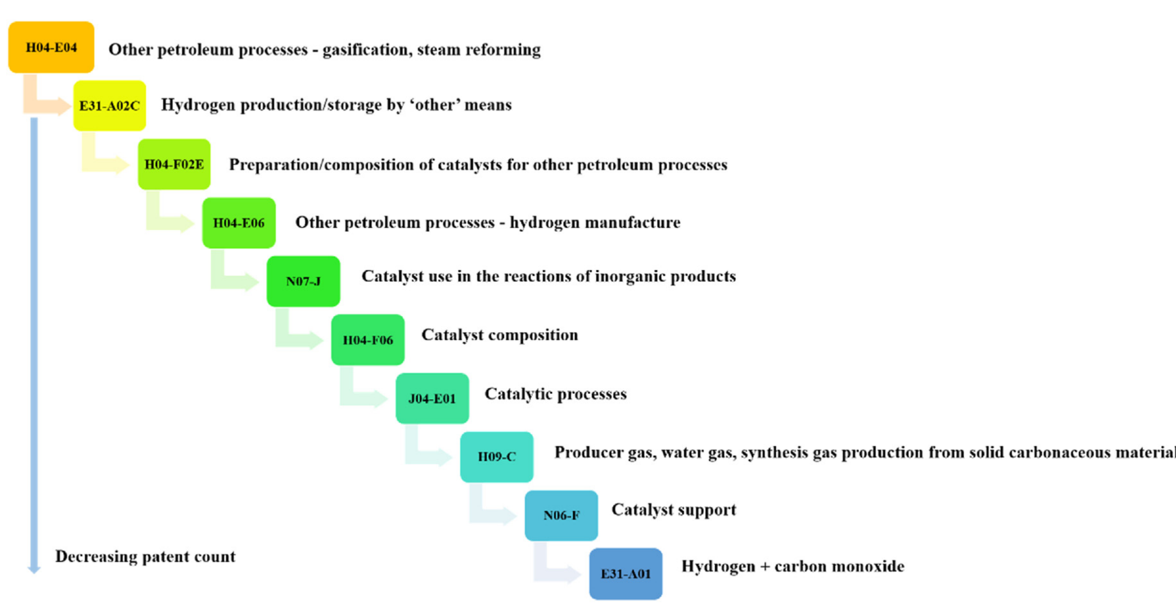

Fig. 18 – Top 10 technical areas under fossil-based technologies.

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reducing/converting carbon monoxide, developing catalysts, enhancing hydrogen separation, reducing energy consumption, lowering the cost of production, controls, polygeneration, and process intensification. Modularization using modern design methodologies (e.g., parametric design), including the application of artificial intelligence, can further lower the cost of fossil-based hydrogen generation. However, these areas have been significantly underdeveloped.

Water-based technologies. As seen in Fig. 20, for hydrogen production by the water dissociation method, electrolysis appears to be the main focus of development ahead of thermolysis and photolysis. Comparing the development of these technologies, thermolysis is growing, photolysis is emerging, whiles electrolysis, on the other hand, is mature. Thus, some developmental highlights in recent years presented in this section will be on the electrolysis method for hydrogen production. In the last five years, the main advances have been in the areas of cell design, electrodes, electrolytes, electrolytic processes, and control methods.

In the area of cell design, Patent No. WO2021115538-A1 reports about a solid oxide cell arrangement such as high-temperature fuel cell assembly and high-temperature electrolytic cell assembly for operating solid oxide fuel cells used in high-temperature fuel cell system or in electrolysis cell system. The design lowers heat losses, resulting in high system efficiency and performance [128]. Development targeted at electrodes is also increasing. Patent No. NL2023775-B1 describes an innovative stack with corrugated (or undulated) electrodes, provides higher currents per unit volume (at the same or similar overpotential and typically pressure drop over the flow channels and thus energy efficiency), such as two times higher than comparable prior art electrolysis systems comprising planar electrodes [129]. Electrolyte film for an electrode of high-temperature hydrogen purification electrolysis is presented in the Chinese patent CN111313069-A. The film has an excellent combination with the substrate, high density, uniformity and stability, and excellent hydrogen barrier performance [130]. For control methods of hydrogen production via electrolysis, Patent No. CN113328639-A showcases such developments. This patent describes a method for controlling high-power electrolysis hydrogen production rectifier power supply. The method has large output power and high hydrogen production efficiency. The output current can be flexibly adjusted in a large range. The system is stable and reliable [131].

In summary, hydrogen production by electrolyzers is a relatively mature technology that has long been utilized in some industrial processes, such as the chloralkali process for producing chlorine (in which hydrogen is produced as a by-product). However, it has not yet been extensively used for specialized hydrogen generation. The current dedicated production of hydrogen via electrolysis is 30 kt per year, representing 0.03% of total hydrogen production. The amount is low because the cost of producing electrolytic hydrogen (USD 3–8/kg H_2) is high when compared to the cost of producing unabated fossil-based hydrogen (USD 0.5–1.7/kg H_2). Closing this gap will necessitate a decrease in electrolyzer costs and, more critically, a decrease in the price of low-carbon power, as

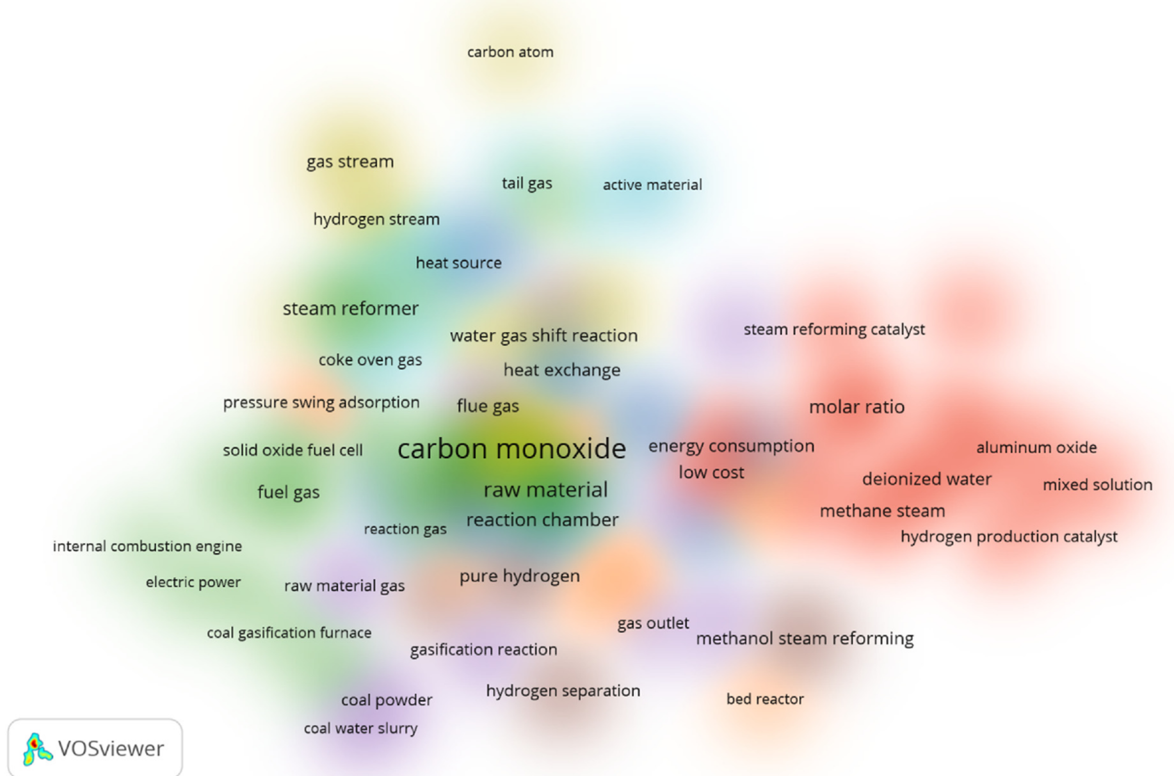

Fig. 19 – Research hotspots of fossil-based technologies in the last five years.

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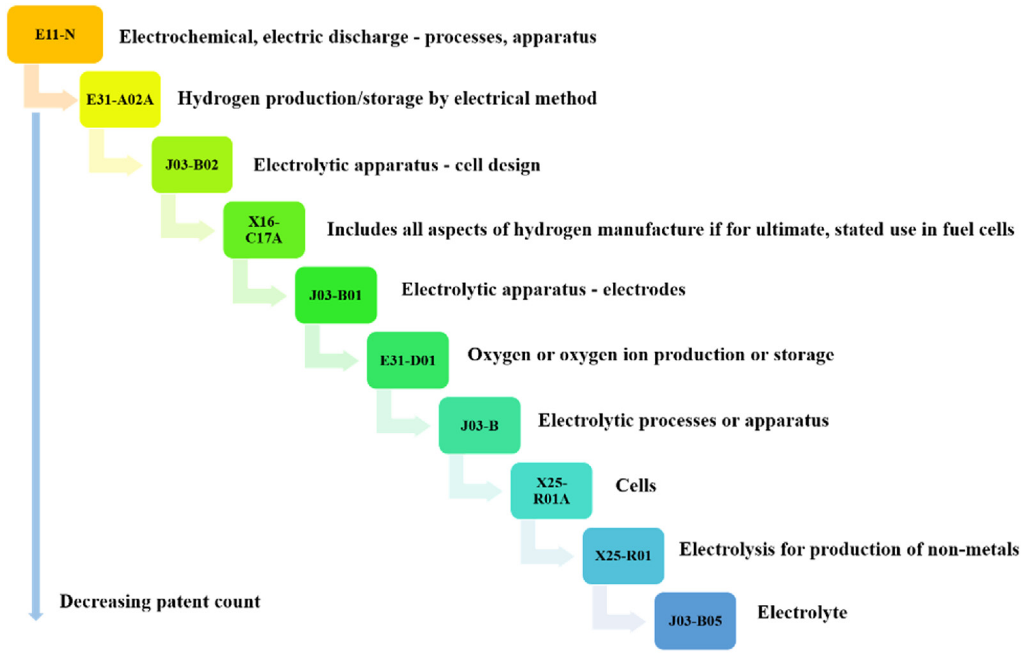

Fig. 20 – Top 10 technical areas under water-based technologies.

well as an increase in load factors [21]. Therefore, recent developments in the area are targeting these aspects of water electrolysis for a cost-effective hydrogen production as seen in Fig. 21. The research hotspots in the water-based hydrogen production methods in the last five years are represented in Fig. 21. Renewable energy (wind and solar) as a source for electrolysis, electrocatalysts, increasing efficiency, reducing energy consumption and cost, prolonging service life, energy-saving system, developing catalyst layer and membrane electrode assembly, protection of electrodes from poisoning, durability and stability, and waste heat recovery are the main hotspot areas of investigation and development in the field of water-splitting for hydrogen production.

Biomass-based technologies. The last five years in the field of bio-hydrogen production have been mainly dedicated to the development of waste-to-energy (WtE) and the development and application of catalysts (Fig. 22). The influence of catalysts in bio-hydrogen production is discussed further with highlights on recent technology developments in the area.

In photo fermentation hydrogen production (PFHP) for instance, the main setback relates to low energy conversion efficiency, resulting from the unstable metabolic products present in PFHP [132]. By obtaining and using a suitable catalyst with stable performance, the problem could be remedied. Also, in microbial electrolysis cell for biohydrogen production, methanogens reduce the yield of hydrogen by competing with electrochemically active bacteria for both substrate and hydrogen. The use of conductive catalysts has been found to severely damage methanogens and promote the disintegration of their cell [133,134]. Moreover, the application of catalysts in gasification alleviates tar pollution, reduce the O_2 content of bio-oil, and regulates the combination of gaseous products [135]. Furthermore, catalysts have the ability to improve hydrogen evolution reaction in microbial electrolysis cells and improve the cell's power density and electrochemical activity [136].

While conventional biomass pyrolysis and gasification processes generate a substantial amount of hydrocarbons and tar, this poses issues in terms of low hydrogen generation, high tar content, and coke deposition [137]. Chemical looping gasification (CLG) is a ground-breaking gasification technique that employs lattice oxygen for gasification via an oxygen carrier (OC) that circulates between the fuel reactor and the air reactor [138]. In this context, patents in the field are developing novel catalytic oxygen carriers. Chinese patent CN107537503-A relates to an oxygen carrier used for preparing biomass synthetic gas. The catalytic oxygen carrier comprises a preset amount of iron oxide, nickel oxide, and lanthanum nickel oxide. The catalytic oxygen carrier has high oxygen carrier activity, biomass gasification rate, and synthetic gas yield and economic efficiency and effectively obtains pure hydrogen gas without a gas separation process [139]. Patent No. WO2018094078-A1 describes a catalyst used to reduce tar from gas mixture or clean condensable hydrocarbons, e.g., tars included in producer gas obtained from biomass gasification. The catalyst comprises nickel, iron, and magnesium oxide. The catalyst provides an easy and economically viable cleaning process [140]. To prevent coke formation, noble metals such as platinum (Pt), ruthenium (Ru), and palladium (Pd) supported on alumina or perovskite-type catalysts are frequently doped with promoters in the hydrogen generation process. Due to the high costs of these noble metals, researchers have begun to substitute them with low-cost and readily accessible metals such as nickel [141]. In the Chinese patent CN110408438-A, a Nickel-based catalyst reinforced molten decoking biomass gasification device is described. The device has good adaptability to biomass raw materials, obtains hydrogen-rich synthesis gas in collecting bag, solves tar byproducts produced in the process of gasifying biomass, and significantly improves the gasification system in energy utilization rate [142].

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The research hotspots in the biomass-based hydrogen production methods in the last five years are represented in Fig. 23. Hotspot areas of investigation and development include preparation and development of advanced and regenerated catalysts, reduction of CO, reducing energy consumption and cost, enhancing gas-solid separation, increasing the yield of hydrogen-rich syngas, improvement in design and operation of bed reactors, waste heat recovery, improvement in design, efficiency, and operation of heat exchangers, advanced utilization of fly ash, and high-temperature biomass conversion.

In summary, the results presented in Results and discussion provide key answers to research questions such as what are the evolutionary trends in the field from 2000 to

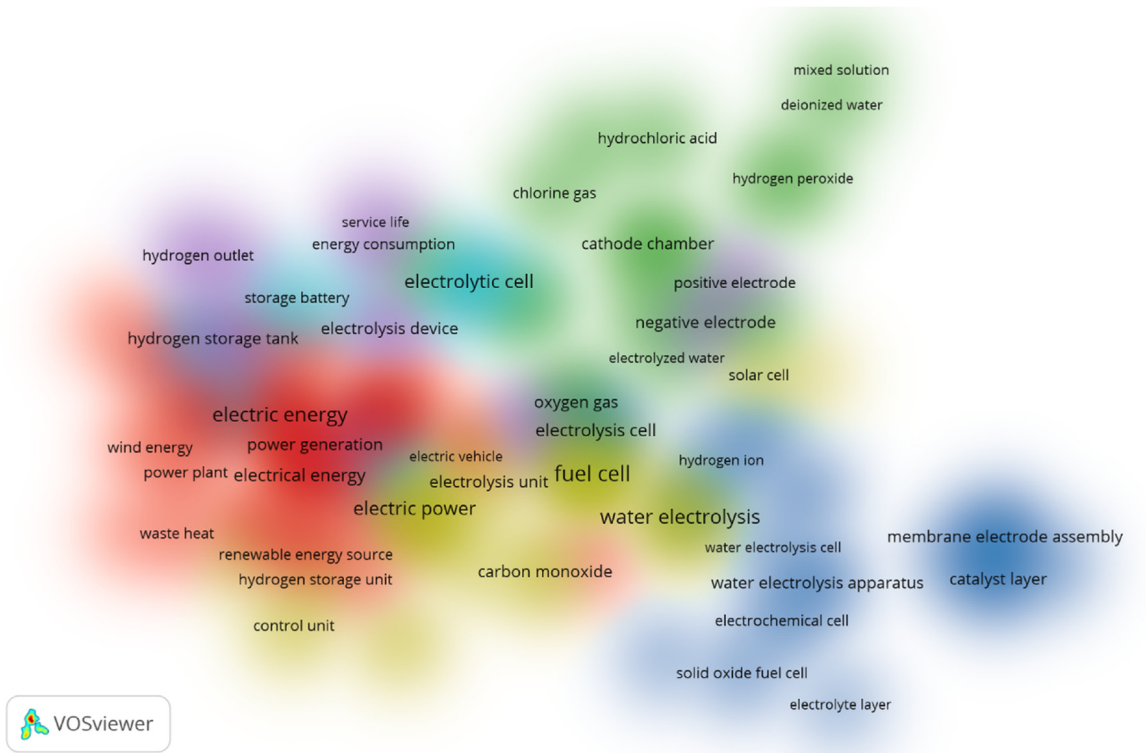

Fig. 21 – Research hotspots of water-based technologies in the last five years.

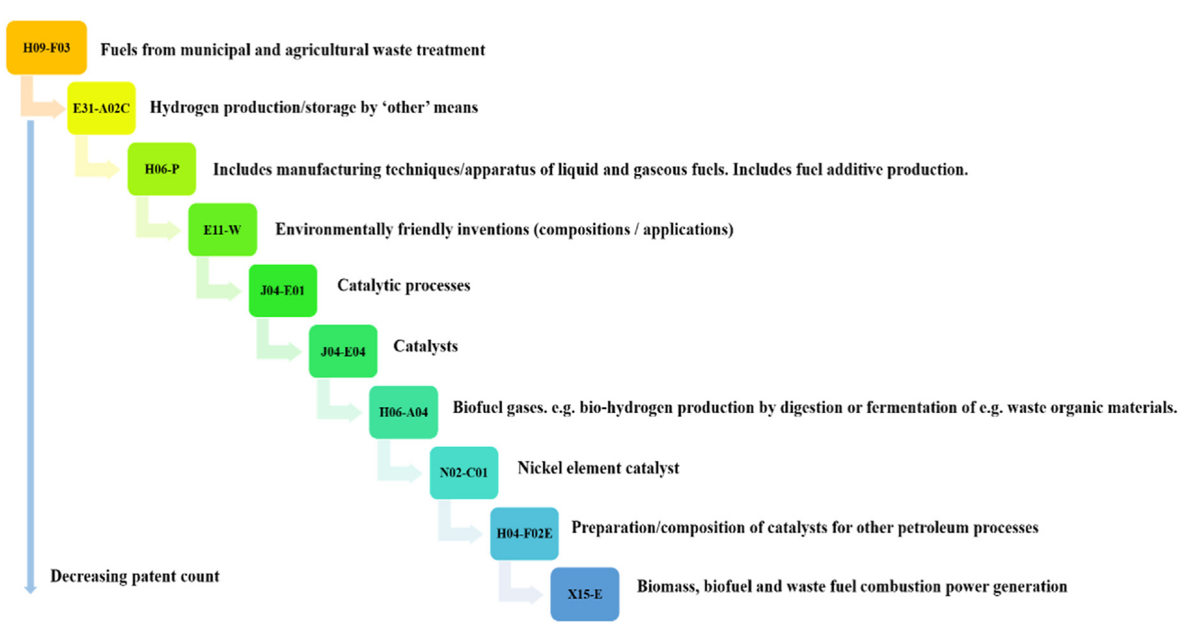

Fig. 22 – Top 10 technical areas under biomass-based technologies.

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2019? Who are the key innovators and assignees in the field during this period? From 1966 to 2019, what has been the technological lifecycle of the two main categories of hydrogen production technologies. Which countries are leading the development of the field? What has the trend been like in the last five years with respect to fossil-based and renewable-based hydrogen production technologies? To the best of our knowledge, this is the only existing study with the latest results on the research hotspots, evolutionary trends, and technological lifecycle of three different types of hydrogen production technologies, i.e., fossil, water, and biomass-based technologies. This is an important addition to the existing studies and has significant potential as a main reference point for the development of the field in the next decade. However, there is one more question yet to be answered, i.e., what are the key enablers for the development of hydrogen production technologies over the study period? The development of every research area hinges on many factors from environmental, technical, economic, and social perspectives. Enablers of hydrogen production technologies presents results for the key enablers of the advancement of the field based on econometric analysis to understand the factors contributing to the development of hydrogen production. These aspects are of great importance to policy and decision-makers concerning the transition toward a hydrogen society.

Enablers of hydrogen production technologies

This study used panel data for six countries US, Japan, Australia, South Korea, China, and Canada. These countries were chosen because they are the most active contributors to the field, as reported in Fig. 5 of the current study. Hydrogen production technology patent applications were used as a proxy for technology development and innovation as done by Zhang et al. [56] and represent our dependent variable. The continuous rise of the world population and rapid economic development, in particular, have resulted in increased daily energy demand, exacerbating the energy problem. Furthermore, the misuse and exploitation of fossil fuels have resulted in major environmental pollution, especially from CO_2 emissions. As a result, most countries are eager to develop renewable energy technologies [143]. Globalization, economic expansion, and industrialization are all encouraged by foreign direct investment (FDI). FDI (inflows) significantly influence technological advancement, production, and growth, as well as the acquisition and development of new knowledge and skills. Inflows of foreign direct investment (FDI) would boost countries' research and development (R&D) and innovation efforts [144]. R&D investment is one of the most important elements impacting technological innovation and transformation, as it reflects a region's R&D scale, as well as its fundamental innovation capability and prospective technological production capacity [145]. Based on the aforementioned discussions, these determinants could influence the development of hydrogen production technologies. Hence, research and development expenditure, GDP per capita (as a measure of economic growth), carbon dioxide emissions, primary energy consumption (fossil fuels, nuclear, renewables), low carbon energy consumption (nuclear and renewables), and foreign direct investment (inflows) were also used as the independent variables. It is worth noting that both primary and low carbon energy consumption were used to respectively identify (1) the effect of total energy demand which is chiefly met by fossil fuels on the progress of hydrogen production technologies, and (2) the independent effect of low carbon fuels on the development of hydrogen production technologies. It is true that factors such as policy development, hydrogen cost and carbon neutral targets could affect the annual changes in hydrogen production development [17]. However, data on these drivers within the study period is unavailable or incomplete, thus excluding them from the analysis. The data on research and development expenditure, foreign direct investment, GDP per capita, and CO_2 emissions were derived from World Bank

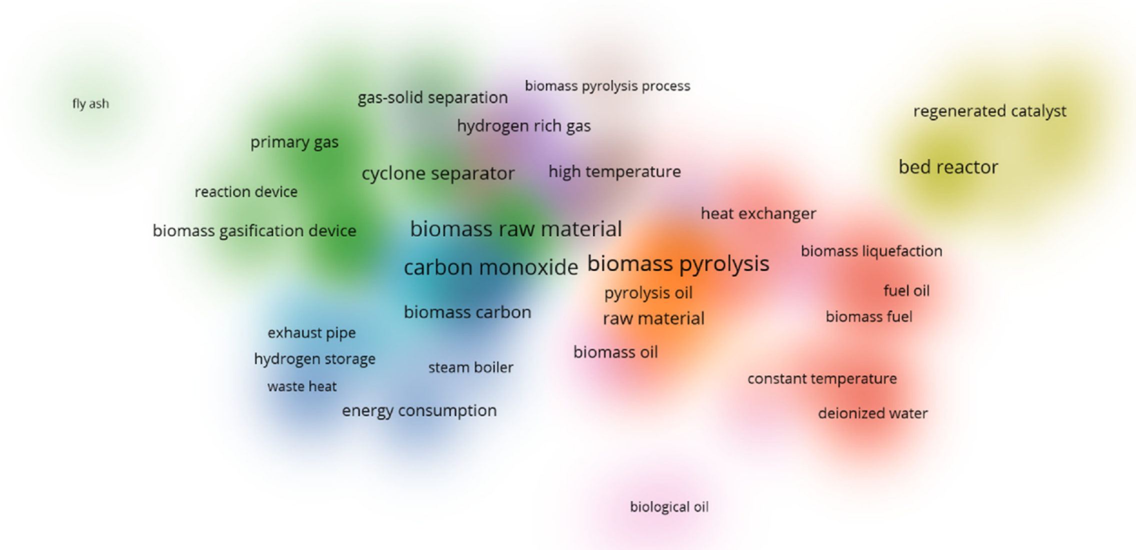

Fig. 23 – Research hotspots of biomass-based technologies in the last five years.

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Indicators [146], and that of primary and low carbon energy consumption were obtained from the British Petroleum Statistical Review [147] and Our World In Data [148], respectively. The study spans 2000 to 2017, covering 18 years period. The analysis was performed for data up to 2017 due to the time lag of approximately 18–20 months from patent filing to publication [61]. Table 4 shows the variable definition and the descriptive statistics. R&D expenditure has the highest mean. This was followed by foreign direct investment, while the hydrogen patent application has the lowest mean. The study does not suffer from outliers since the standard deviation of the variables is below the mean.

The country-specific averages of the variables are shown in Table 5. It is observed that Japan leads in hydrogen production patent applications, as already reported, while the US occupies the first position for R&D expenditure, GDP per capita, fossil and low carbon energy consumption, and foreign direct investment. China is the main CO_2 emitter among the six countries under study.

The correlation relationship among the variables is shown in Table 6. R&D expenditure, carbon dioxide emissions, and energy consumption strongly correlate with hydrogen production development. Foreign direct investment has a weak positive correlation with hydrogen production development, while economic growth has an insignificant negative correlation with hydrogen production development. However, correlation does not necessarily guarantee a causal relation. As such, further analysis is needed to reveal the impact of the independent variables on the development of hydrogen production technologies.

Fig. 24 shows the bivariate relationship between R&D expenditure, economic growth, carbon dioxide emissions, primary energy consumption, low carbon energy consumption, and the development of hydrogen production technologies. The results confirm the correlation matrix in Table 6.

Empirical model

This study estimates the following empirical model (Equation (4)) with reference to the approach used in Appiah-Otoo et al. [149] on the relationship between crowdfunding and renewable energy generation:

$$\ln pat_{it} = b_0 + b_1 \ln rnd_{it} + b_2 \ln gdp_{it} + b_3 \ln co_{2it} + b_4 \ln ene_{it} + b_5 \ln lce_{it} + b_6 \ln fdi_{it} + \varepsilon_{it} \quad (4)$$

where $\ln pat_{it}$ represents hydrogen production technology patent applications serving as the dependent variable. We added research and development expenditure ($\ln rnd_{it}$), economic growth ($\ln gdp_{it}$), carbon dioxide emissions ($\ln co_{2it}$), primary energy consumption ($\ln ene_{it}$), low carbon energy consumption ($\ln lce_{it}$), and foreign direct investment ($\ln fdi_{it}$) as the control variables. Here i represents countries, t is time, and ε represents the error term.

Econometric results

This study first assessed the cross-sectional dependence among the variables because of the short period. As shown in Table 7, the results show that except for primary energy consumption, the rest of the variables are cross-sectionally dependent (correlated across the countries under study). Thus, to address this problem, this study used the panel-corrected standard errors (PCSE) technique for the empirical analysis. This model produces robust standard errors [150]. The study further used the feasible generalized least squares (FGLS) estimator for our robustness analysis. This technique also addresses cross-sectional dependence problems [151].

The PCSE results are reported in Table 8. The variables were added sequentially to check their robustness. R&D expenditure has a statistically significant positive effect on the development of hydrogen production technologies in all the models. Also, low carbon energy consumption significantly enhances the hydrogen development of hydrogen production technologies, as shown in Model 6. Moreover, Model 6 and Model 4 also respectively show that the increasing levels of CO_2 emissions and primary energy consumption will lead to the creation and development of more hydrogen production technologies. Economic growth significantly reduces the growth of hydrogen production technologies, as shown in Models 2–5. Similarly, foreign direct investment also impedes the development of hydrogen production technologies, as depicted in Model 6. The above results from PCSE are consistent with that of FGLS, as shown in Table 9, further emphasizing the robustness of our results.

The embryo phase of every technology is characterized by economic losses and high prospects of failure and can only usher into the growth phase if, most importantly, R&D investments increase. The beneficial impact of research and development spending on hydrogen production methods is that the likelihood of a given technology failing decreases, and development continues. The link between research and development and innovation is complicated. For a country to become more innovative, public investment in R&D is critical. Countries with greater levels of public investment in R&D and

Table 4 – Descriptive statistics.

Variables	Definition	Unit of measurement	Obs.	Mean	Std. Dev.	Min	Max
lnpat	Hydrogen production technology patent applications	–	108	3.832	0.973	1.609	5.598
lnrnd	Research and development expenditure	US$	100	24.941	1.216	22.602	27.034
lngdp	Economic growth (GDP per capita)	US$	108	10.092	1.023	6.866	11.130
lnco2	Carbon dioxide emissions	kt	108	14.074	1.164	12.733	16.12
lnene	Energy consumption	TWh	108	8.733	1.082	7.180	10.501
lnlce	Low carbon energy consumption	TWh	108	6.594	1.320	3.871	8.479
lnfdi	Foreign direct investment (inflows)	US$	105	24.403	1.417	20.12	26.96

Obs., observations; Std. Dev, standard deviation; Min, minimum; Max, maximum.

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Table 5 – Country-specific averages of variables.

Country	lnpat	lnrnd	lngdp	lnco2	lnene	Lnlce	lnfdi
Australia	2.754	23.626	10.614	12.830	7.309	4.271	24.224
Canada	2.987	23.911	10.575	13.205	8.217	7.140	24.209
China	4.207	24.890	8.080	15.737	10.090	7.524	25.614
Japan	4.915	25.787	10.572	13.992	8.659	6.475	22.982
South Korea	3.501	24.173	9.948	13.185	7.955	5.976	22.974
US	4.628	26.673	10.763	15.496	10.165	8.178	26.249

Table 6 – Correlation matrix.

Variables	lnpat	lnrnd	lngdp	lnco2	lnene	lnlce	lnfdi
lnpat	1						
lnrnd	0.783***	1					
lngdp	−0.00361	0.299**	1				
lnco2	0.642***	0.689***	−0.415***	1			
lnene	0.652***	0.724***	−0.335***	0.986***	1		
lnlce	0.561***	0.659***	−0.0807	0.756***	0.852***	1	
lnfdi	0.202*	0.461***	−0.121	0.711***	0.718***	0.593***	1

$*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

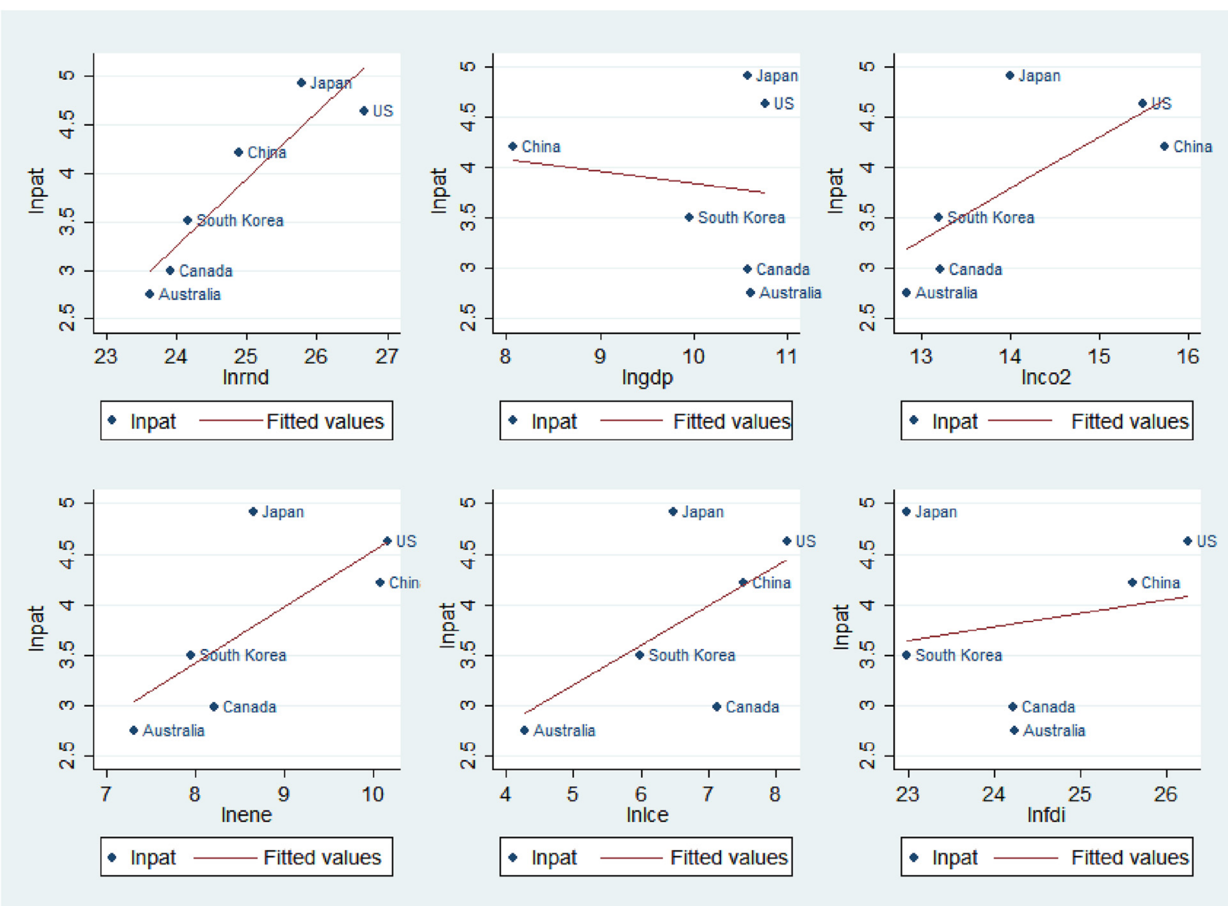

Fig. 24 – Bivariate relationship between research and development, economic growth, carbon dioxide emissions, primary energy consumption, low carbon energy consumption, foreign direct investment, and hydrogen production technology patent applications.

Table 7 – Cross-sectional dependence.

Variables	CD-test	p-value
Lnpat	4.050***	0.000
lnrnd	12.780***	0.000
lngdp	11.710***	0.000
lnco2	1.950**	0.051
lnene	0.790	0.430
lnlce	5.350***	0.000
lnfdi	4.830***	0.000

*p < 0.1, **p < 0.05, ***p < 0.01.

a better knowledge base have higher spending efficiency. R&D spending has a beneficial impact on public policies, such as regulatory, monetary, and tax policy, procurements, standards, workforce human capital, and market access - all of which are significant aspects of creating an environment that encourages innovation [152]. The volume of knowledge available to researchers influences the rate of innovation, and the degree of knowledge is determined by previous cumulative R&D efforts. As a result, in the long run, R&D investment is the most important element in determining the amount of innovation [153]. Voutsinas et al. [153] argue that a 1% increase in total R&D expenditure would raise Greece's innovation by approximately 1.87% in the long run. Likewise, according to Pegkas et al. [152], a 10% increase in higher education R&D expenditure will foster innovation by 1.2%–1.8% in the EU. This is in tandem with our current findings, i.e., from Tables 8 and 9, it is observed that a 1% increase in R&D expenditure would increase innovation on hydrogen production technologies by 1.29% in Model 5. Therefore, government officials and policymakers must have keen interest in R&D expenditures if net zero carbon emissions were to be reached via hydrogen fuel.

The negative impact of economic growth on hydrogen production technologies could be attributed to the fact that an

Table 8 – Determinants of Hydrogen production technology patent (Panel-corrected standard errors results).

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Lnrnd	0.687***	0.724***	1.265***	1.273***	1.286***	0.868***
	(0.030)	(0.032)	(0.094)	(0.115)	(0.126)	(0.185)
Lngdp		−0.187***	−0.652***	−0.671***	−0.664***	−0.253
		(0.045)	(0.092)	(0.155)	(0.159)	(0.198)
lnco2			−0.625***	−0.753	−0.168	1.788**
			(0.084)	(0.555)	(0.632)	(0.778)
Lnene				0.129	−0.696	−2.511***
				(0.526)	(0.699)	(0.889)
Lnlce					0.190	0.580***
					(0.127)	(0.152)
Lnfdi						−0.207***
						(0.071)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−13.413***	−12.525***	−12.380***	−11.720***	−14.374***	−17.425***
	(0.728)	(0.628)	(0.657)	(2.482)	(2.796)	(3.628)
Observations	100	100	100	100	100	98
R^2	0.753	0.788	0.846	0.846	0.849	0.869

Standard errors in parentheses, *p < 0.1, **p < 0.05, ***p < 0.01.

Table 9 – Determinants of Hydrogen production technology patent (Generalized Least Squares results).

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Lnrnd	0.687***	0.724***	1.265***	1.273***	1.286***	0.868***
	(0.042)	(0.040)	(0.095)	(0.096)	(0.096)	(0.143)
lngdp		−0.187***	−0.652***	−0.671***	−0.664***	−0.253*
		(0.045)	(0.086)	(0.093)	(0.093)	(0.135)
lnco2			−0.625***	−0.753***	−0.168	1.788***
			(0.102)	(0.272)	(0.518)	(0.681)
lnene				0.129	−0.696	−2.511***
				(0.255)	(0.674)	(0.845)
lnlce					0.190	0.580***
					(0.144)	(0.184)
lnfdi						−0.207***
						(0.060)
Time dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−13.413***	−12.525***	−12.380***	−11.720***	−14.374***	−17.425***
	(1.040)	(0.986)	(0.842)	(1.549)	(2.528)	(2.968)
Observations	100	100	100	100	100	98

Standard errors in parentheses, *p < 0.1, **p < 0.05, ***p < 0.01.

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increase in GDP implies an increase in energy demand. Future trends show a shift towards clean hydrogen production ahead of fossil-based production technologies as a result of carbon-neutral targets. Based on the current cost of green hydrogen relative to fossil fuel prices, technology readiness, and current energy structure, among other issues inherent in green hydrogen production, this would imply that fossil fuels must meet the majority of this increase in energy demand. This eventually reduces the relative growth of hydrogen production as the production of fossil fuels increases. As such, policymakers should make a conscious effort to find the right mechanisms to continue the development of green hydrogen production technologies amidst the higher pressure for conventional energy resources. The present work's negative impact of GDP on the development of hydrogen production innovation is consistent with previous works. The long-lasting elasticity findings of Kumaran et al. [154] indicate that there is a significant negative impact of GDP on the consumption of renewables in ASEAN countries. Similarly, using panel unit root tests and the system generalized technique of moment estimation, Basak [155] points out that GDP had a negative impact on the consumption of renewable energy in the Balkans between 1998 and 2011.

Summary of significant findings

In summary, the current investigation has revealed that the patent activities in the field are growing steadily at an annual growth rate of 4.21%, with the most recorded growth occurring in the first decade of the study period. Japan, the USA, and China are the frontrunners in the field, seeing to the development of hydrogen production technologies as demand for the fuel is expected to increase six-fold by 2050 compared to 2020 levels in the NZE scenario. Basically, over the last two decades, the research hotspot for development can be categorized into three main groups; (1) fuel cells and electrical means of hydrogen production, (2) hydrogen production by methane and methanol steam reforming, and (3) end product from hydrogen production. Fossil-based technologies for hydrogen production are the most advanced, with a technology maturity rate of about 66% compared to approximately 57% of renewable-based technologies. The last five years have shown great attention to developing renewable-based technologies compared to fossil-based technologies with 67% and 33% of patent applications, respectively. The main development in fossil-based hydrogen production in the last five years is targeted at the development of novel catalysts, enhancing hydrogen separation, and reducing/converting carbon monoxide. For electrolysis, the inclusion of wind or solar energy in the electrolysis process is significantly ongoing. Efforts are also being made to reduce the cost of production, develop electrocatalysts, and protect electrodes. Innovators in the field of biomass for hydrogen production are focusing on developing novel catalysts, reducing CO emissions, energy consumption, and cost, whilst the increasing yield of hydrogen-rich syngas is also of great importance. R&D expenditure has had the most positive impact on the growth of hydrogen production technologies since the start of the 21st century.

Key challenges and future perspective on hydrogen production

It is obvious that considerable changes to the present energy system are required if global carbon neutrality targets are to be fulfilled. Hydrogen as a fuel offers a path to achieving a low-carbon society. However, unlocking the whole promise of hydrogen necessitates a commitment to ongoing research and development, as well as scaling up demonstrations and deployments alongside the private sector. Unfortunately, the majority of traditional technologies for producing hydrogen from fossil fuels are coupled with significant environmental degradation and high energy consumption. As a result, greater emphasis has been placed on the deployment of innovative technologies for hydrogen generation from renewable and nuclear sources, with increasingly stringent and applicable environmental protection rules in place across the world [156]. Water electrolysis, biomass gasification, and nuclear thermal/chemical pathways are examples of such technologies. Green hydrogen has the potential to cut carbon emissions, but only if the major hurdles, including the cost of production technologies, system durability, reliability, infrastructure, and safety, are addressed [33].

The high production costs of green hydrogen are the primary impediment to the growth of a worldwide clean hydrogen industry. Hydrogen is subject to market demand preferences and competition from other energy sources in the energy market. Green hydrogen production costs are currently too high to compete economically with other energy sources or hydrogen generated from fossil fuels, limiting the development of a worldwide clean hydrogen market. Reports also suggest that hydrogen generation from fossil fuels will continue to be the most cost-competitive alternative through 2030. Low-carbon hydrogen is, in fact, significantly more expensive than grey hydrogen: green hydrogen costs $ 2.5–5 per kilogram, blue hydrogen costs $ 1.50–3.50 per kilogram, and grey hydrogen costs roughly $1.50 per kilogram [157]. In addition, the life of equipment such as electrolyzer modules is about one-third (10 years) of the design life of a hydrogen production facility (typically 30 years). This results in increased operating expenditure and a longer turnaround duration due to the necessity to replace a number of electrolyzer modules in the cell house regularly to maintain installed production capacity [158]. Similarly, another major impediment to the establishment of a low-carbon hydrogen economy is the lack of an established clean hydrogen value chain. Currently, the hydrogen value chain is dominated by fossil fuels, with just a few pilot projects on low-carbon hydrogen. A worldwide clean hydrogen market would thus necessitate the development of whole new value chains. The primary problem is deciding which method to adopt because hydrogen may be produced in a variety of ways. The biggest problem in terms of production will be deciding whether to use green, blue, or yellow hydrogen. While all of these approaches produce low-carbon hydrogen, they have varied consequences in terms of infrastructure, industry, and, most critically, the environmental effect [157]. Green Hydrogen Technology makes use of renewable energy sources such as the sun and wind to produce hydrogen, which is used as a source of water splitting.

The inability of renewable energy to be available 24/7 is a constraint on its use. As a result, operating electrolyzer modules for hydrogen generation at baseload capacity is problematic. Battery reserve power storage is insufficient to cover the power needs of the electrolysis plant (cell house) and hydrogen compression [158]. Large-scale biohydrogen production is likewise hampered by two major drawbacks: poor yield and high production costs. Furthermore, the production of by-products during dark fermentation is a concern for large-scale biohydrogen generation, which might lead to waste management issues [159].

Aside from the obvious technical, commercial, and regulatory impediments to hydrogen production, there are issues with public awareness and comprehension. To proactively communicate the value of hydrogen to the public, community acceptance of hydrogen as a 'green' alternative to energy distribution will need to be pushed through focused engagement efforts. Misconceptions about the safety and usage of hydrogen must be addressed, as well as the gas's environmental credentials as a tool to decarbonize the present energy system [31,160].

Going forward, some common research development and demonstration thrusts for hydrogen production (both fossil and renewable sources) include: "New catalysts and electrocatalysts with reduced platinum group metals; Modular gasification and electrolysis systems for distributed and bulk power systems; Low-cost and durable membranes and separations materials; Novel, durable, and low-cost thermochemical and photoelectrochemical materials; Accelerated stress tests and understanding of degradation mechanisms to improve durability; Reduced capital costs for reforming technologies, including auto thermal reforming (ATR); Improved balance-of-plant components and subsystems, such as power electronics, purification, and warm-gas cleanup; Component design and materials integration for scale-up and manufacturability at high volumes; Reversible fuel cell systems including for polygeneration of electricity and hydrogen; System design, hybridization, and optimization, including process intensification" [161].

Conclusion and recommendations

Over the next decade, global greenhouse gas emissions need to be cut by 25–50% to meet the 2015 Paris Agreement goal of containing global warming to 1.5–2 °C. These targets call for immediate action, especially in the manner and rate at which fossil fuels are consumed. Hydrogen has shown tremendous promise as a future alternative fuel, and as such, its production technologies have received a lot of interest in recent years. Understanding the tendencies of evolution is critical for policy and corporate decision-makers in order to make appropriate decisions. Thus, this research aimed to trace the technological evolution of hydrogen production technologies and analyze the key enablers using patent and econometric tools. Key findings from the current work are reported as follows.

The main patents identified are in the field of hydrogen production by 'other' means (e.g., steam reforming), fuel cells (general), hydrogen production by electrical means, and catalyst used in the production of hydrogen. About 60% of the patents were deposited between 2000 and 2010, with 2006 being the most active patenting year. In the last two decades, Japan, the US, and China have recorded the most patent contributions toward hydrogen production development. Companies mainly drive the patenting activities in these countries, while academic institutions exhibit weak global competitiveness. Based on the feedstock-based comparative assessment, fossil-based technologies' technology maturity rate was roughly 66%, compared to approximately 57% for renewable-based technologies. This suggests that, in comparison, the growth of fossil-based hydrogen generation technologies is essentially stationary, with limited room for further expansion. On the other hand, renewable-based technologies offer a higher potential for technical advancement and quick expansion. In the last five years, China has remained the most active contributor in all three categories of technologies (i.e., fossil fuel, water, and biomass-based technologies). In addition, the trend shows that recent advancements in the field (last five years) are more geared towards water-based (60.3%), followed by fossil-based (33.2%) and biomass-based technologies (6.5%) for hydrogen production. Unlike water-and-fossil-based technologies, universities and research institutions dominate biomass-based hydrogen production technologies; hence, the progress to the commercialization of these technologies is relatively immature. As expected, in the last five years, steam reforming, electrolysis, and pyrolysis continue to be the main developmental areas under fossil-based, water-based, and biomass-based hydrogen production technologies, respectively. Also, in the last five years, production and development of novel catalysts for generating hydrogen from fossil and biomass sources are advancing, whiles progress in the field of water-splitting in the same period has mainly targeted electrode, cell and electrolyte development.

Further results show that research and development expenditure and low carbon energy consumption have a statistically significant positive effect on the development of hydrogen production technologies. In addition, the increasing levels of CO_2 emissions and primary energy consumption will lead to the creation and development of more hydrogen production technologies, but the effect is not as significant as R&D expenditure. Conversely, economic growth and foreign direct investment impede the development of hydrogen production technologies. Investing more in hydrogen production (R&D expenditure) appears the most effective enabler to developing the field and should therefore be prioritized.

The current work is not spared from limitations. Patent searches were undertaken from 2000 until December 2019. Thus, developments before the 21st century have not been accounted for. Also, patents that were not found in the Derwent Innovation database (DII) were excluded. Prospectively linked patents that were not referenced in the patent title or abstract keywords were not included either. Furthermore, owing to database restrictions, a few non-English full patents were not accessible, and data was based on abstracts and claims that were only available in English. These specifications may have led to the exclusion of relevant patent documents on the reviewed subject. The search strategy by keywords and filtering is also subjective and was mainly according to the investigators' discretion following the works of previous studies in the field. However, we do not anticipate a significant deviation from the current results obtained if these limitations were to be addressed. Future works can combine multiple databases such as DII, ESPACENET, USPTO, etc., to trace the technological advancement in other aspects of the hydrogen economy such as storage, transport, and end-use.

To summarize, the current study adds to the ongoing discussion about hydrogen production from the standpoint of technological trends. The existing reviews have already taken significant steps in this direction, but they are distinguished by a lack of current trends, restrictions on individual hydrogen production sources, a limited application area, or reviewed stages beyond the production stage (such as storage). The current study closes these gaps by identifying the technological life cycle of both fossil and renewable hydrogen production technologies. In this study, econometric tools were used for the first time to determine the key drivers behind the field's development. As far as we are concerned, this is the first study in the field of hydrogen energy research to combine patent-life cycle analysis with econometric analysis. The current work could be crucial as a reference point for the field's development and emerging studies over the next decade.

Credit author statement

Jeffrey Dankwa Ampah: Writing – Original draft preparation, formal analysis, investigation. **Chao Jin**: Supervision, Methodology.: **Islam Md Rizwanul Fattah**: Conceptualization, Writing – Reviewing & Editing.: **Isaac Appiah-Otoo**: Formal analysis.: **Sandylove Afrane**: Data curation, formal analysis, software.: **Zhenlong Geng**: Validation.: **Abdulfatah Abdu Yusuf**: Writing – Reviewing & Editing.: **Tongtong Li**: Software.: **T. M. Indra Mahlia**: Writing- Reviewing & Editing.: **Haifeng Liu**: Funding acquisition, Writing – Reviewing & Editing.

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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