ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Review Article

Patent analysis on green hydrogen technology for future promising technologies

Donguk Yang [a,b,*], Juhaeng Lee [c], Nicholas Chaehoon Song [b], Sangseon Lee [d,e], Sangkyu Kim [a], Sukho Lee [f], Seongim Choi [b,1,**]

[a] Korea Electric Power Corporation (KEPCO), Naju, South Korea
[b] Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea
[c] Gwangju Institute of Green-Car Advancement (GIGA), Gwangju, South Korea
[d] Korea Institute of Industrial Technology (KITECH), Gwangju, South Korea
[e] Chonnam National University (CNU), Gwangju, South Korea
[f] Green Energy Institute (GEI), Mokpo, South Korea

HIGHLIGHTS

- Comprehensive analysis of 5,471 patents in the areas of green hydrogen energy from year 2002 to 2022.
- Classification of water electrolysis (ALK, PEM, AEM, SO, ALL) and system operation (BOP, CON).
- Natural Language Process (NLP) method for automatic parsing of the patent database.
- Patent trends by year, country, technology type, applicant, and technology life cycle.
- Patent analysis methods of network analysis, co-citation, and VOS visualization.

ARTICLE INFO

Article history:
Received 16 December 2022
Received in revised form
23 April 2023
Accepted 26 April 2023
Available online xxx

Keywords:
Green hydrogen
Water electrolysis
Patent analysis
Network analysis
Technological forecasting
Artificial intelligence(AI)

ABSTRACT

Technology trend studies on patent analyses of hydrogen technology are critical in understanding the status of present and future technology, as well as, its market opportunity. However, the studies were mostly limited to specific countries and lacked the details of green hydrogen production technology. In this study, a patent analysis forecasting future green hydrogen technology was carried out. To make the patent database for the analysis, first, a comprehensive survey on green hydrogen projects worldwide was conducted and hydrogen-related technologies were classified into two network categories of the stand-alone and the grid-connected type, as well as three options for renewable energy resources, Energy Storage System (ESS) and hydrogen utilization type. More than a thousand patents during the past twenty years on green hydrogen technology were directly collected from the Worldwide Intellectual Property Service (WIPS) website using quantitative and qualitative searches. The patents were classified into two technology types, water electrolysis and system operation, and seven technology areas within two types. The patents were further analyzed according to year, country, technology area, and major applicants. Overall, the technology type of system operation accounts for 53% compared to water

* *Corresponding author*. Korea Electric Power Corporation (KEPCO), Naju, South Korea
** *Corresponding author*. Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea
E-mail addresses: kre100@kepco.co.kr (D. Yang), schoi1@gist.ac.kr (S. Choi).
[1] Current address: 123 Cheomdangwagi-ro, Gwangju, South Korea.

https://doi.org/10.1016/j.ijhydene.2023.04.317

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

electrolysis, which indicates that companies are more focused on system integration and control strategies rather than green hydrogen production. Furthermore, the four commercial water electrolysis types were analyzed to predict the near-term trend, showing that the Alkaline (ALK) and Polymer Electrolyte Membrane (PEM) approaches are at the stage of entering maturity, while Anion Exchange Membrane (AEM) and Solid Oxidation (SO) approaches are still in the early development stages. In addition, AEM approach shows fewer patents and applicants, indicating a lower entry barrier to the market. Lastly, the three most impactful patents in the world were identified for each of the seven technology areas.

Contents

Introduction

The report from the 5th Intergovernmental Panel on Climate Change (IPCC) in 2014 announced that recent global climate change is highly related to human activities [1]. Countries around the world have quickly acted on the issues by modifying their economic policies on clean energy resources and exploring new markets for renewable energy. For example, China, as the world's largest carbon-emitting country, has

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

Abbreviations

AEM	Anion Exchange Membrane Water Electrolysis
AI	Artificial Intelligence
ALK	Alkaline Water Electrolysis
ALL	All types of Water Electrolysis(Repetitively)
BOP	Balance of Plant
CEA	Commissariat Energie Atomique
CON	Control Strategy
CPC	Cooperative Patent Classification
EM	Expectation-Maximization
ESS	Energy Storage System
FCM	Fuzzy C-Means
IEA	International Energy Agency
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
KIPO	Korean Intellectual Property Office
MEM	Membrane Electrode Assembly
NLP	Natural Language Process
P2G	Power-to-Gas
PEM	Polymer Electrolyte Membrane Water Electrolysis
SO	Solid Oxidation Water Electrolysis
SPC	Search Path Count
URL	Uniform Resource Locator
WIPS	Worldwide Intellectual Property Service
WO	World intellectual property Organization

focused on the modification of infrastructure technologies through eco-friendly vehicles, renewable energy production, and energy-efficient buildings [1]. The transition to renewable energy sources, such as wind and solar power, is crucial for reducing greenhouse gas emissions and mitigating the impacts of climate change. Hydrogen is considered a promising energy carrier for a low-carbon future, as it can be produced from renewable sources and used in various sectors, including transportation and industry. However, challenges such as high costs and infrastructure development still need to be addressed. Several countries, including Germany, China, Japan, South Korea, India, Australia, Morocco, Oman, Saudi Arabia, and the United Arab Emirates, are investing heavily in hydrogen research and development. While hydrogen has all the characteristics of an ideal future fuel, there are still challenges that need to prevail for it to become a widely used fuel source, potential barriers such as production costs, storage, and transportation infrastructure, safety concerns related to handling hydrogen gas, and the need for more efficient fuel cells [93–95].

Overall, it is most important to take strategic action to promote carbon-neutral technologies to mitigate the climate crisis and lower the political influence that tends not to take responsibility for carbon emissions. Carbon neutrality should be applied to all fields of science and engineering where carbon is emitted as a byproduct or main product, with the target fields not limited to science and technology. According to the International Energy Agency (IEA), the most effective way to achieve carbon neutrality lies in the conversion of low-carbon energy, such as a fossil fuel-based one, to renewable energy [1]. However, renewable energy such as solar and wind power greatly depends on the dynamic nature of the environment, and the variability in power output is becoming a gradual problem. One example can be seen in Jeju Island, South Korea, where the amount of wind-energy curtailment gradually increased up to 1,301 MWh caused by increasing renewable energies [2]. It is necessary to secure an efficient energy storage and management technology to efficiently handle the inconsistency in the power output from renewable energy.

On the other hand, the Power-to-Gas (P2G) concept is a promising technology enabling conversion from the surplus electrical energy produced by renewable energy resources into chemical energy such as hydrogen and methane. Hydrogen is recently expected as an energy-carrying medium for the future in low-carbon and low-heat forms and is drawing great interest within energy industry fields. While a key mechanism for hydrogen production is water electrolysis, grey hydrogen is the most popular form of hydrogen production, but is not free from carbon emission due to the steam reforming process from fossil fuels and its byproduct [3]. Green hydrogen is truly carbon-neutral combined with solar and wind power resources.

It is pivotal to introduce the core technology of green hydrogen; water electrolysis. Water electrolysis is the process of breaking water molecules down into hydrogen and oxygen using electrical energy. In this paper, four commercial types of water electrolysis are introduced, which are Alkaline (ALK), Polymer Electrolyte Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxidation (SO) as suggested by the International Renewable Energy Agency (IRENA) [38]. Each type of electrolyzer has its distinct characteristics and advantages, and the selection of an appropriate type depends on various physical, chemical, and electrochemical aspects. Alkaline electrolyzers are the oldest and most widely used technology for water electrolysis. In 1900, the first industrial electrolyzer based on the filter-press design was proposed by Dr. Schmidt [98]. Since then, more than 400 electrolyzers were mainly used in industrial applications to produce hydrogen and oxygen for welding or cutting applications, and ammonia as precursors of fertilizer and explosives. The first very large-scale electrolyzer, a 125 MW plant that could produce 27,900Nm3/h of hydrogen, was built by Norsk Hydro in 1927 in Vemork, Rjukan [99]. The principle of alkaline electrolysis is based on the use of an alkali electrolyte, typically potassium hydroxide (KOH), and the use of two electrodes, an anode, and a cathode, to create an electrochemical reaction. Alkaline electrolyzers operate at relatively low temperatures and can produce high-purity hydrogen. However, they have relatively low efficiency and require high maintenance due to their use of corrosive alkaline electrolytes. PEM electrolyzers, also known as Proton Exchange Membrane (PEM) electrolyzers, were developed in the 1960s as an alternative to alkaline electrolyzers. DuPont de Nemours developed the copolymers which are called Nafion, and it has a lot of scientific interest [100]. In PEM electrolysis, a solid polymer electrolyte membrane is used to conduct protons between the anode and cathode. This results in a more efficient and flexible system, as the use of a solid polymer electrolyte membrane allows for the use of pure water and avoids the need for a corrosive electrolyte. PEM electrolyzers also operate at lower temperatures than alkaline electrolyzers, and can be quickly started and stopped, making them ideal for use in intermittent renewable energy systems such as solar and wind power.

AEM electrolyzers are a newer technology that uses an Anion Exchange Membrane (AEM) to conduct negatively charged hydroxide ions between the anode and cathode. This results in a system that is more efficient and has a higher purity level of hydrogen than alkaline electrolysis while avoiding the corrosive nature of the electrolyte used in alkaline electrolyzers. AEM electrolyzers also operate at lower temperatures than SO electrolyzers, making them more suitable for certain applications. SO electrolyzers are a more recent development that uses a ceramic oxide material as the electrolyte. SO electrolyzers operate at high temperatures and produce high-purity hydrogen with high efficiency. This makes them suitable for applications that require high-purity hydrogen, such as fuel cell applications. However, SO electrolyzers also face significant challenges due to the high temperatures required for operation, which can lead to material degradation and decreased efficiency over time.

In addition to the different types of electrolyzers, the selection of components and materials depends on the type of electrolysis system and the operating conditions. For example, ALK, PEM, and AEM operate at a temperature below 100 °C and atmospheric pressure, while SO operates above 700 °C. Also, ALK uses nickel-based electrodes, while PEM uses platinum-based electrodes. The selection of materials and components can have a significant impact on the efficiency and durability of the electrolysis system. Because each technology has its challenges, from critical materials to performance, durability, and maturity; there is no clear winner across all applications, which means that the strategic plan for developing all types of water electrolysis technology is important. In this regard, patent-based technology analysis is necessary for understanding the maturity of the technology and its commercial aspects.

Various reports have been published on patent-related analysis over a long time. The majority of studies in the past were conducted outside of hydrogen technology areas [4–16]. Some articles carried out literature surveys on hydrogen-related studies with a focus on the hydrogen storage area [17,18], entire technology areas of hydrogen energy [19–22], or hydrogen energy as a supportive technology of the fuel cell [23,24]. Notable reviews on hydrogen production technology are as follows. Hwang et al. analyzed the water electrolysis technologies for hydrogen production in four countries from 1997 to 2005 [25]. Patent analysis of a bio-hydrogen technology was conducted by W. Lai et al. [26]. Similarly, Hsu et al. [27–29] and C. Olivo et al. [30] studied hydrogen production from biomass. Martinez-Burgos et al. investigated a wide range of hydrogen production technologies by three patent database systems including documents written in three languages [31]. Very recently, J. D. Ampah et al. investigated the patent trend of hydrogen production with a comparison among water-based, fossil-based, and biomass-based technologies [32].

The main purpose of the aforementioned hydrogen-related R&D projects is to fully understand the development and direction of this field and to estimate the value of specific technology setting future research of advanced hydrogen production in certain countries [25,27–32]. At the company level, their purpose is not only to identify technological competitors but to identify technological hotspots and vacuums because it is possible to determine trends in technological development and predict potential directions in the development of new technology [25,30]. At the national level, governments can plan for technological development and simulate scenarios for future emerging technologies by analyzing technical information associated with patents [27–29,31,32]. As a result, they provide insight into technical details, business trends, and industrial innovation plans that might be needed for political investment or corporate mergers and acquisition strategies.

The patent analysis methods were comprehensively reviewed by A. Abbas et al. [33]. For the patent analysis methods, they are predicting technological trends in terms of technology areas, publication years, countries, and applicants. The methods are also diverse with recent data-driven approaches based on text mining and a Natural Language Process (NLP). Recently, numerous research articles were published on the development of text mining techniques [4–6,9,11–13,17,19,21,23] and patent network visualization techniques [4,6,9,11,13–15,17,21,32,89]. To create a list of selected patents in matrix form from tens of thousands of various patent documents, common strategies not only utilize commercial tools including ITGInsight, and VantagePoint [5,17,32], but also create scripts using interfaces with Python, Linux, or R [4,6,9,11–13,19,21–23]., The NLP-based method has proven effective in processing large documents containing textual data [34,35]. On the other hand, there is an approach to directly access the website of the patent database, parse specific sentences, and write out into the pre-defined form for analysis. F. Rizzi et al. [19] and M. Baumann et al. [22] carried out patent analysis based on this approach.

For post-processing of the analysis results, network analysis with visualization of the relationship among patents gives an insight as well as forecasts the technology for policy-making [8,36]. Popular approaches are the co-occurrences network [4,11,13,15,17,21] and the neural network method [11] for finding keywords including the International Patent Classification (IPC) and creating other search operation terms. Other approaches include the citation network [4,6,9] and co-patentee [11,14] methods. Some software tools that can be used for visualizing networks are reviewed by A. S. Mendonca et al. [37], and include VOSviewer [6,32], Gephi [9,17], and UCINET 6 [14,15]. For data clustering, methods of k-means clustering [4], Expectation-Maximization (EM) algorithm [13], and Fuzzy C-Means (FCM) [28] are applied to enhance the network visualization. On the other hand, to identify future technology pathways, a trajectory analysis method using the Search Path Count (SPC) algorithm [6], technology life cycle with S-curve [8,24], and Power-law distribution theorem [9,17] are proposed for analyzing the future technology pathway.

Novelty methods of the problem

Most of all, the novelty of the present study focuses mostly on the details of the hydrogen production of water electrolysis types, and the patent database is collected from a total of 157 countries. This is distinctively different from previous studies where the majority of the patent analysis on hydrogen-related

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

technologies and articles dealt with a wide range of sectors but did not focus on the details of hydrogen production by the water electrolysis techniques [4–32]. In addition, some production articles are limited to specific countries [25–30] hence patent analysis regarding the hydrogen production of water electrolysis has not yet been covered all over the world. More specifically, the technology of green hydrogen production is classified into two technology types, water electrolysis, and system operation. These two types are divided into four subtypes of commercial hydrogen production methods, and two subtypes for system integration as well as a control method, respectively. Based on these classifications, patent analysis, and network analysis are conducted.

And then the way to define search keywords, target countries, and search period is unique from previous studies by other researchers [19,22]. The present study utilizes the three levels of searches to refine the patent data at high accuracy. Especially, keywords are defined by the preliminary study investigating the multiple green hydrogen projects shown in Appendix A. The initial search has been carried out based on the selected keywords in Appendix B as well as the codes of International Patent Classification (IPC) and Cooperative Patent Classification (CPC). To cover all countries in the world, we selected WIPS as a patent database [39,90]. We also put into consideration the twenty years duration of patent rights for developers to provide a state-of-the-art patent map [91].

Furthermore, the present study suggests the network analysis of green hydrogen production through a new type of web mapping method. For pre-processing, previous NLP approaches based on the downloaded patent document naturally suffer from the search through the data in an unstructured format, written in different languages, and inherently contain semantic ambiguity amongst the structures [34,35]. Since the recent patent data were already electronically published on the public website with well-structured formats throughout all the patent data, we tried to map into the data through the web locations containing the Uniform Resource Locator (URL) [92]. Instead, we developed a Python script to directly access the patent website WIPS and parse out the patent database by various search criteria which will be discussed in Section Materials and Methods.

Last but not least, we also discuss two methods of post-processing to recognize the high-impact patents as a technical barrier in green hydrogen technologies. Firstly, VOS visualization with co-citation analysis has advantages to getting relations between forward and backward among surveyed patents. Secondly, high-impact patents are qualitatively discussed by specific criteria with every seven areas of three highly impactful patents, which will be discussed in Section Impact Index for Effective Patents. It is noteworthy to mention that high-impact patent analysis is a better option because of affecting more criteria metrics than network analysis. These evaluations can be important for understanding the current and future status of green hydrogen technology and its market opportunities.

Brief summary

The structure of this paper is as follows. In Section Materials and Methods, a classification of key technology areas and a new type of methodology for the patent database of green hydrogen production are effectively investigated. Technology focus types in green hydrogen production, either in water electrolysis or in system operation. Section Results and Discussions discusses the results of patent analysis and network analysis. Patent trends by year, technology area, country, applicant, and technology life cycle are discussed, and then network analysis is considered through the methods of co-citation and VOS visualization. We then analyze the models through a developed program for predicting the technological barriers and market entries. Through the technology trend analysis, future research directions can be projected with perspectives on the technical impacts. Lastly, conclusions are explained in Section Conclusions.

Materials and methods

For the evaluation of the trend of technology and markets, patents over the past twenty years have been directly collected with the method of noise filtering, and web scraping and then analyzed using patent analysis and network analysis. These analyses can be important for understanding the current and future status of green hydrogen technology and its market opportunities.

To collect patents related to green hydrogen technologies, a wide range of research and development (R&D) projects concerning hydrogen are extensively searched as shown in prior to the present patent analysis. Project information including project year, energy resource type, types of water electrolysis, the energy storage system (ESS), the utilization of the hydrogen, and its progress status are summarized, and they can also be classified into two network types of stand-alone and grid-connected [46–88].

A key technology of green hydrogen production is water electrolysis, and its four commercial productions, such as ALK, PEM, AEM, and SO, are mainly discussed in this section. For geological diversity, a total of four continents are selected, and all relevant patents are collected by an extensive search from the patent database website which is publicly available. They are focused mostly on the registered patents during the past twenty years from January 2002 to June 2022. The present study targets a total of seven technology areas as described in the next sub-section in the patents and research outcomes to evaluate their potential contributions to the green hydrogen production research area.

The online patent database service of Worldwide Intellectual Property Service (WIPS) [39] was chosen mostly due to its open access. WIPS is South Korea's first company that provides worldwide patent information online with the company's patent data collected from patent offices in various countries. It is officially approved by the Korean Intellectual Property Office (KIPO) as a professional survey organization for cumulative technology data following patent laws. Both quantitative and qualitative searches are carried out, respectively, to classify the patents either by statistical estimation of specific categories or by technical keywords related to the technical contents of an individual patent.

As depicted in Fig. 1, the flow chart for the analysis of green hydrogen production technology is presented. The 5,471 patent data extracted from WIPS is pre-processed in Section Data Classification Methods and analyzed for a total of 1,305 valid patents. Based on the analysis techniques in Section Patent Data Analysis Methods, the technology trend by years, applicants, and life cycle are reported. Also, it is expanded to 3,939 patents through co-citation networks and visualized through VOS visualization. Therefore, core patents, technology maturity, and entry barriers give insight into the production of green hydrogen technology.

Classification of green hydrogen technology

Green hydrogen technology was classified into two technology types and seven technology subtypes, or technical areas as shown in Table 1. This paper introduces two technology types, water electrolysis of alkaline (ALK), Polymer Electrolyte Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxidation (SO), and system operation of Balance of Plant (BOP) and Control Strategies (CON). Water electrolysis is central to green hydrogen technology, and classified into four technology subtypes for the commercial production of ALK, PEM, AEM, and SO as suggested by International Renewable Energy Agency (IRENA) [38]. If a specific production technology is found repetitively, a new subtype is defined with corresponding an abbreviation ALL. In addition, a technology subtype of the system operation is defined independently, as there are a large number of system integration technologies of electric or mechanical subsystems. The descriptions of the seven technology subtypes, or technical areas, of green hydrogen technology are as follows.

As seen in Table 2, ALK water electrolysis comprises an alkaline solution, two electrodes, and a membrane (or diaphragm) allowing the passage of OH- ions. PEM water electrolysis was developed to overcome the drawbacks of the low-power alkaline type. The central component is the MEA (Membrane Electrode Assembly) which comprises a membrane allowing the passage of proton H+ ions coated on each side with a catalyst based on expensive metal (often platinum, iridium, and ruthenium) as well as the electrodes. AEM water electrolysis takes advantage of both ALK and PEM technologies with less harsh environments of alkaline and the simplicity of PEM electrolysis structure, but a membrane allows the passage of OH- ions. SO water electrolysis uses a hard, ceramic compound for the electrolyte and two

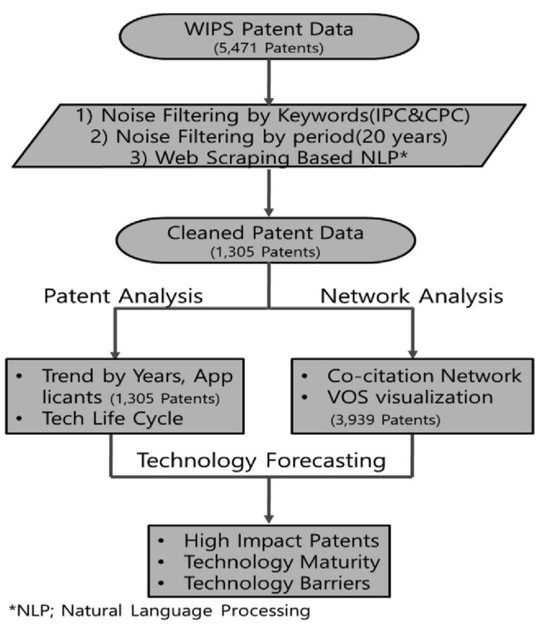


Fig. 1 – Flow chart on patent analysis of green hydrogen production field.

Table 2 – Description of Technical Subtype (Area) classification.

Technology Subtype (Technology Area)	Description
Alkaline Water Electrolysis (ALK)	Hydrogen production through alkaline (OH-) water electrolysis
Polymer Electrolyte Membrane Water Electrolysis (PEM)	Hydrogen production through water electrolysis resistant to acidic (H+) environment.
Anion Exchange Membrane Water Electrolysis (AEM)	Hydrogen production through water electrolysis based on the MEA resistant to alkaline (OH-) in a single node of anode or cathode
Solid Oxidation Water Electrolysis (SO)	Hydrogen production through water electrolysis is resistant to high-temperature environments.
All types of Water Electrolysis (ALL)	Hydrogen production can be repetitively applicable to commercial technologies despite stack-level water electrolysis.
Balance of Plant (BOP)	System integration of Electric BOP (E-BOP) and Mechanical BOP (M-BOP)
Control Strategy (CON)	A strategy for the safe operation of the system with enhanced efficiency.

Table 1 – Classification of Technology.

Technology	Technology Type	Technology Subtype, or Technical Area	Abbreviation
Green Hydrogen Technology	Water Electrolysis	Alkaline Water Electrolysis	ALK
		Polymer Electrolyte Membrane Water Electrolysis	PEM
		Anion Exchange Membrane Water Electrolysis	AEM
		Solid Oxidation Water Electrolysis	SO
		Repetitively applicable to Water Electrolysis	ALL
	System Operation	Balance of Plant	BOP
		Control Strategy	CON

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

electrodes, and its process is both chemically stable in terms of the oxidization of O2- ions and mechanically stable when operating under high-temperature conditions. ALL represents the water electrolysis technology that applies to more than one water electrolysis type with good scalability in stack levels.

The BOP includes the electrical and mechanical components to integrate the hybrid system, whereas the CON technology targets the safe operation of a whole system to improve system efficiency. In our study, all of these technologies investigated the number of related patents by discussing them from the patent information.

Data classification methods

Patents collected from the database of WIPS [39] are classified both quantitatively and qualitatively to define technology trends of green hydrogen in various aspects of technology subtypes and economic impacts.

Quantitative classification

First, quantitative classification is carried out with the search operation term defined by the Boolean operators as shown in Appendix B. The numbers of patents are counted by the publication period, country, title, technology subtypes, Uniform Resource Locator (URL) and an applicant, etc. extracted to Microsoft Excel. These amount to a large number of data and serve as the baseline data to study the green hydrogen technology trends worldwide with relevant technology subtypes.

Qualitative classification

Qualitative classification is carried out by three sequential search steps to enhance the accuracy of the patent data of interest. After the initial keyword-based search, data with noise is filtered out in the title, abstract, and claim of the patents based on the WIPS database.

In the first level of the search, the combination of both the keywords and the International Patent Classification (IPC) codes is employed. The keyword-based search is the most intuitive, as keywords are selected based on the domain experts' knowledge and intuition [8]. They are extracted in the present study from the literature survey of the existing research articles on internal combustion engine technologies. The IPC-based search enables convenient access to the technology classifications [22], and allows smooth transitions in the data collection. The extended cooperative patent classification (CPC) codes are defined to extend the range of the hydrogen production codes as shown in Tables 3 and 4 after the recently introduced Cooperative Patent Classification (CPC) classes are compared with the IPC classes in terms of technical relevance. Also, any noise in the collected data is filtered to remove the patents with keywords that are not relevant to green hydrogen technology. Especially, the patents before 2002 are removed, as they expired after the effective date of the patent.

Subsequently to the first search, the web scraping method is conducted during the next step to investigate the detailed contents of the patent data. The method parses specific patent data from the URLs, enables classification of the patent data by the criteria of interest, and improves the quality of the patent dataset for trend analysis.

Patent Data Analysis techniques

Three methods for patent analysis are utilized: technology life cycle, visualization through network analysis, and patent high-impact index.

Technology life cycle

The technology life cycle is a method that is useful for short-term prediction of a specific technology in consideration of future direction and competitiveness with other technologies [42,96,97]. Due to the huge expense of research and development stages, the estimation of the technology life cycle could save money on whether its product has a long lifespan. The technology life cycle consists of five stages, research and development, growth, maturity, recession, and resurrection.

Table 3 – Extracted international patent classification (IPC) [40].

Initial IPC Code	Description	Extended IPC Code
B01D*	Separation	C01B*, C07C*, C07D*,
B01J*	Chemical or Physical Processes	C08G*, C12P*, C22C*,
C02F*	Treatment of Water, Waste Water, Sewage, or Sludge	C23C*, C25C*, C25D*,
C25B*	Electrolytic or Electrophoretic Processes for the Production of Compounds or Non-Metals	H02J*, H02P*
G01R*	Measuring Electric Variables	
H01 M*	Processes or Means	

Table 4 – Extracted cooperative patent classification (CPC) [41].

Initial CPC Code	Description	Extended CPC Code
C01B-0003/00	Hydrogen; Gaseous mixtures containing hydrogen;	Y02E-0070/00, Y02E-0070/30, Y02E-0060/32, Y02E-0060/30,
Y02E-0060/36	Hydrogen production from non-carbon containing sources, e.g. by water electrolysis	Y02E-0060/34, C25B-0001/02
C10J-2300/1684	with electrolysis of water	
C25B-0001/04	by electrolysis of water	
C25B-0001/042	by electrolysis of steam	

For example, smartphone suppliers would consider that the technology life cycle of competitive smartphone types affects profits to gain intellectual property rights. In the present study, the ratio of the number of patents to applicants was suggested for every 5 years during the past 20 years, resulting in a total of four technologies of ALK, PEM, AEM, and SO for the life cycle analysis. A global trend in technology development can be predicted by analyzing the life cycle of green hydrogen technology for the past 20 years.

Network analysis

Although a large number of technical keywords are extracted from the patent dataset, the prediction of the technology by keywords alone is limited since the correlations among green hydrogen technologies in technology evolution by years and technical areas cannot be analyzed by keywords alone. A network analysis with visualization is carried out to figure out how technology is related in terms of derivation and inheritance.

Network analysis is a method to identify forward and backward relations of a specific patent to others. Those relations are defined as backward where a specific patent is derived or differentiated from other patents from previous years, or forward if a specific patent in consideration is cited by patents in following years. All individual patents have both forward and backward relations, and their strength is defined by the number of citations.

These relations are automatically and promptly found by a Python script that carries out the aforementioned three-step searches for specific patents corresponding to pre-specified technical keywords in WIPS and writes them into an external file in CSV format. This citation-based analysis is effective in identifying high-impact patents, as almost all patents in the dataset have forward and/or backward relations. VOSviewer was also used for visualization of the correlation network as the software is open to the public with detailed instructions [43].

VOSviewer includes the objects of interest such as search terms or keywords. Between the two search terms, it creates a link based on the citation and referral, and the strength of each link is calculated by a numerical value, which is directly indicative of the number of other patents in forward and backward relations. If a search term or a technology area is at least one citation made by or it makes other patents, the weight of occurrences concerning counterpart patents is calculated and expressed in the VOSviewer. The strength of the relations between two patents i and j in the network is defined by a simple mathematical form as shown in equation (1):

$$AS_{i,j} = \frac{C_{ij}}{C_i C_j} \quad (1)$$

where $AS_{i,\,j}$ represents the ratio between the number of simultaneous citations of patents i and j and the multiplication of the citation counts made by patents i and j, respectively [44]. This way, technology similarity and positive correlation between any patents are determined, and a group of patents with large correlation strengths can be combined into a cluster. Overall, technology search terms and keywords are grouped into numerous clusters, developing a network with technology areas and various links altogether.

Impact index for effective patents

High-impact patents are defined in the present study by the impact scores shown in Table 5, which take into account the number of patents in a forward relation, the number of family patents, registration, and the duration of the remaining period of the registration. A point scale is assigned proportionally to the total count for each criterion as shown in Table 5.

The number of forwarding patents is defined by the number of citations made by other patents and is considered to be directly proportional to a high impact. The forward citation refers to subsequent patents citing a specific patent based on the criterion in Table 5. That is, the quality and technological influence of a specific patent are estimated by identifying how many other patents have cited that patent. The family patent is defined as the patent granted simultaneously in domestic and foreign countries. If the number of foreign countries that grant the patent is large, it is regarded as a highly valuable technology and assigned a higher point value. If the patent is currently registered, despite not being open to the public, it is assigned certain points. The longer the patent has a registration period till the expiration, the higher points are assigned. Overall, all points are summed up to calculate the impact score for an individual patent.

Results and discussions

Definition of dataset

The patent dataset from the WIPS database and the valid patents among surveyed patents are classified by each country for further analysis, as shown in Table 6. Overall, 5,471 patents are extracted for the analysis and valid

Table 5 – The criterion of classifying important patent.

Criteria	Counts	Points
Number of forward citations	0–5	0.5
	5–10	0.7
	10–15	0.8
	15–20	1.0
	20–30	1.2
	30–40	1.3
	40–50	1.4
	>50	1.5
A number of foreign countries were published as well as the domestic country.	1–2	0.5
	3–4	0.7
	5–9	0.8
	10–15	1.0
	16–20	1.2
	21–25	1.4
	>25	1.5
Registration	Registration	1.0
Duration of the remaining registration (Year)	Expired	0.5
	1	1.0
	2–3	1.1
	4–5	1.2
	6–7	1.3
	8–9	1.4
	>9	1.5
Total	–	1.5–5.5

Table 6 – Number of patents classified by the major countries.

Country	Patent	Valid Patent
South Korea (KR)	390	64
China (CN)	2,532	519
Europe (EP)	426	128
United States (US)	732	196
PCT (WO)	721	207
Others	670	191
Total	5,471	1,305

patents are 1,305 among them. Then patents are categorized in chronological order from the effective date of the registration period. A total of 5,471 patents are classified in Table 6 by the major countries of South Korea, China, Europe, the United States (U.S.), Patent Cooperation Treaty (PCT), and others. PCT is assisted by the World Intellectual Property Organization (WIPO), an abbreviation of WO, for their international inventions and helped patent offices with their patent-granting decisions simultaneously in a large number of countries. The number of countries sharing PCT amounted to 157 nations such as Australia, China, South Africa, etc [45]. The valid patents can be classified by the aforementioned seven technology areas with a total of 1,305. Such valid patents are classified to analyze the technology trends in the following sections by the metrics of year, technology area, country, and applicants with the Origin and Excel tools. In addition, four key technology areas in water electrolysis type are further analyzed in terms of technology maturity to predict the future direction for research and development.

Green hydrogen technology trend by years

Patent trend by technology areas

The global patent trend of green hydrogen by technology areas (or technology subtypes) during the recent 20 years has been presented. The technology type of the system operation showed a ratio of 53% as shown in Fig. 2(a), while that of the water electrolysis has less than 50%. The result reveals that the technology type of system integration containing control strategy and balance of plant areas had a growth in the total counts of patents than that of water electrolysis. We have obtained an interesting result that companies in the hydrogen industry focus more on the technology type of system operation, rather than traditional individual technology areas for water electrolysis.

Furthermore, it is noteworthy to mention a growing number of patents over the past five years in the four technology areas (subtypes) in Fig. 2(b) to produce and commercialize green hydrogen. Technology areas of the alkaline (ALK) and PEM are the majority consisting 64% of all, followed by SO and AEM. This makes sense because the majority of green hydrogen projects, from our earlier study summarized in Appendix A, are observed as technology areas of ALK and PEM. Among those four major technology areas, it is clear that ALK and PEM are dominant as shown in Fig. 2(b). A trend increase of PEM patents in recent few years is believed that companies may have a huge interest in the PEM technology area.

Patent trend for major countries

We will discuss the global patent trend by major countries during the past 20 years from Jan. 2002 to Jun. 2022. As can be seen in Fig. 3, there seems to be a notable increase since 2015 in the number of green hydrogen patents. China shows the growth in the hydrogen market since 2014, with a dramatic increase made since 2019. Out of countries including China, Europe, S. Korea, the U.S., and PCT nations, China holds about 40% of the total patents, followed by the PCT (WO) with 16%. It is shown that green hydrogen production technology is being developed mostly in countries of large economic size, with international patents in PCT showing a gradual increase. Since 18 months are generally considered before the patent is applied to the public, recent patents are not included in present data, and its decrease shown in 2022 should not be interpreted as a problem.

Patent trend in technology areas for individual country

In Fig. 4, patents are categorized by the technical areas of green hydrogen for the top four countries of China, the U.S., Europe, and PCT nations, which include the largest number of

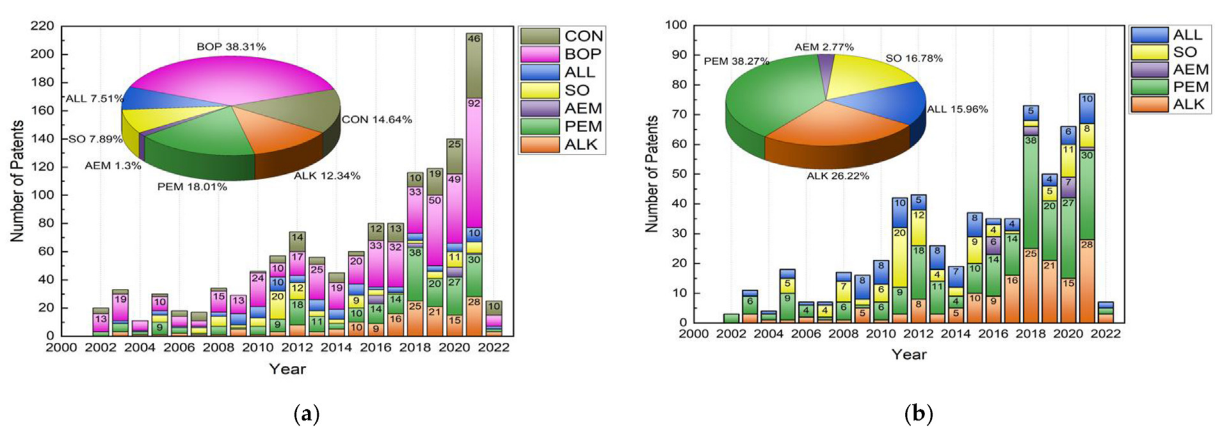


Fig. 2 – (a) Patent trend in all seven technology areas; (b) patent trend in the technology areas of water electrolysis.

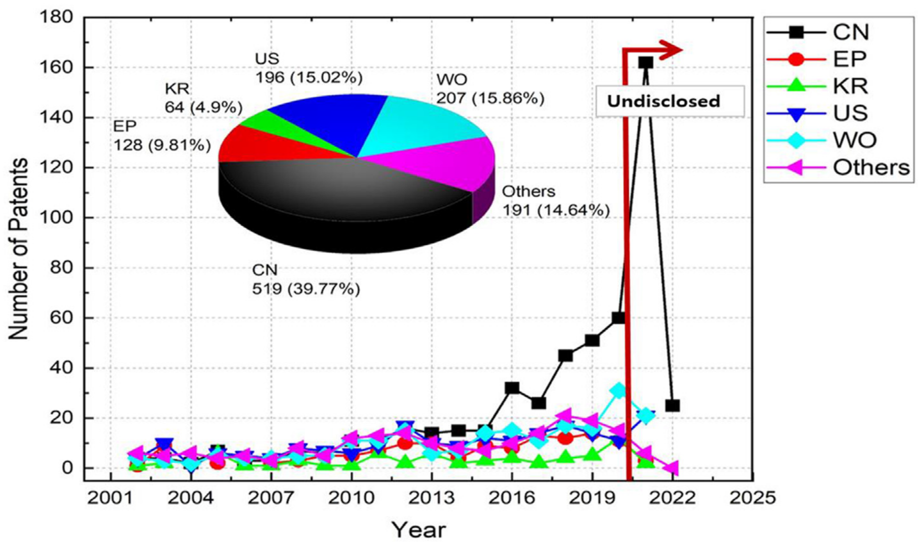


Fig. 3 – Patent trends by years of green hydrogen production.

patent applications in the world. From Fig. 4(a), it can be seen that China sees a consistent increase in the number of patents with a more dramatic increase in the technology type of system operation. The commercial technology subtype, or technology area, for hydrogen production, is expanding with more focus on the ALK and PEM. It is interesting to be seen that more patents in the SO area around 2011 in Europe as shown in Fig. 4(c), which indicates that the traditional technologies have been further advanced and accompanied by fuel cell technologies [99]. In Fig. 4(b) and (d), PCT nations and the U.S. also have an increasing number of patents when compared to 20 years ago. Furthermore, a gradual increase in the patents on technology type of system operation is observed over technology type of water electrolysis.

Patent trend by patent applicants

In this section, we will discuss patent trends by applicant companies of which a total of 547 commercial companies are surveyed based on the referred technical reports and literature. Major applicant companies are decided for major countries and classified by technology areas respectively. It is

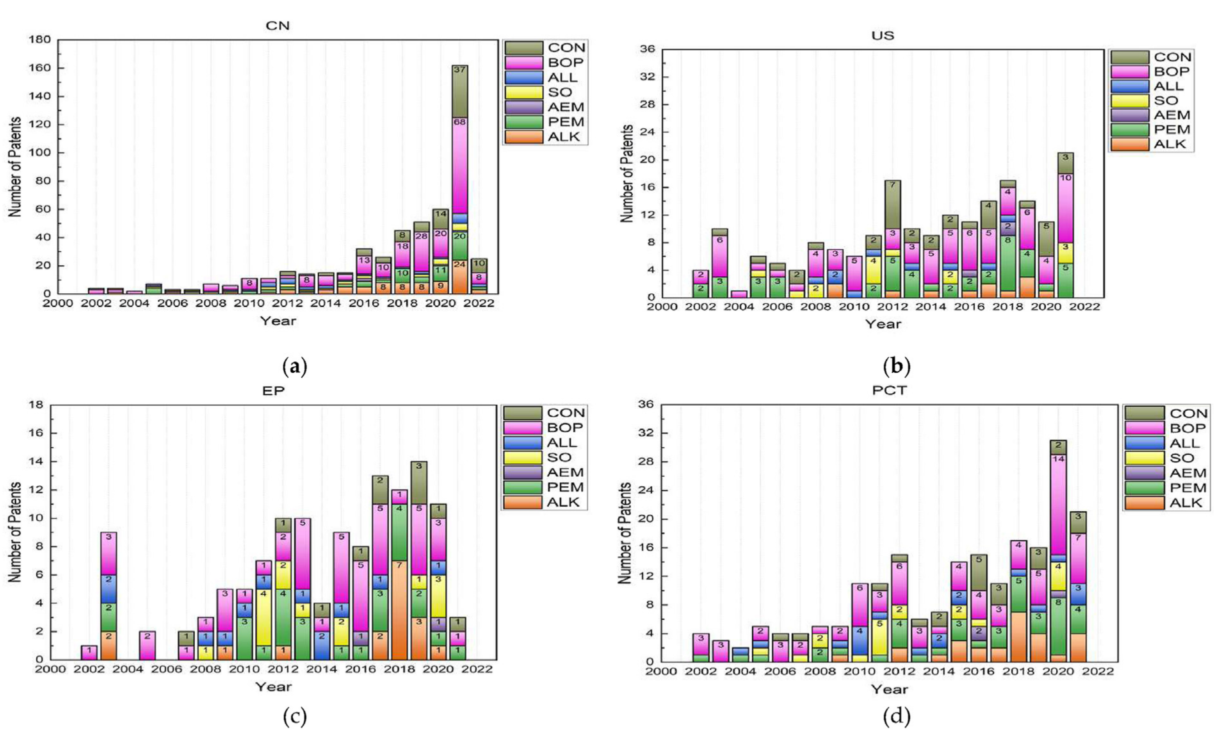


Fig. 4 – Patent trends by major countries: (a) China; (b) U.S.A; (c) Europe; (d) PCT;

noteworthy to mention that there may be some unseen applicant companies that do not want to share their patents hence the information of such companies has limited access to the public.

Patent trend by patent applicants for major countries

The top ten applicant companies and their patent applications per technology areas are shown in Fig. 5 for the major four countries of China, the U.S., Europe, and PCT nations. In China, shown in Fig. 5(a), Huaeng clean energy research institute produced as many patents as 36, followed by 18 from Sungrow power supply, and 17 from Tsinghua University. Other than those, a total of seven companies including the Panasonic corporation had 61 patent applications. It is shown that Huaeng clean energy research institute holds the most patents of all, especially patents in the technology area of BOP rather than that of water electrolysis areas. Overall, from the analysis of the top ten applicants, China holds more patents in the technology areas of BOP and CON.

Next, U.S. as shown From Fig. 5(b), Honda motor has as many patents as 29, followed by 14 from Panasonic corporation and 9 from Plug power. Other seven companies including Toshiba hold some patents. Honda motor accounts more patent in the technical areas of the BOP and CON, rather than other technical areas regarding the green hydrogen production. It can be also summarized from the top ten applicants that U.S. hold more patents in technology areas of BOP and CON. On the other hand, in Fig. 5(c) for Europe, Japanese company of Asahi Kasei is leading in the patent application, while Siemens energy and Panasonic are working on the technology development. These companies are identified as major applicants in the countries sharing PCT nations as shown in Fig. 5(d).

In summary, Fig. 5 shows that global companies are already applied to major markets, particularly in China, U.S., and Europe. Among companies, Panasonic, Asahi Kasei, and Simens Energy recorded the highest number of patents. Notably, Japan and Germany have more patent rights in terms

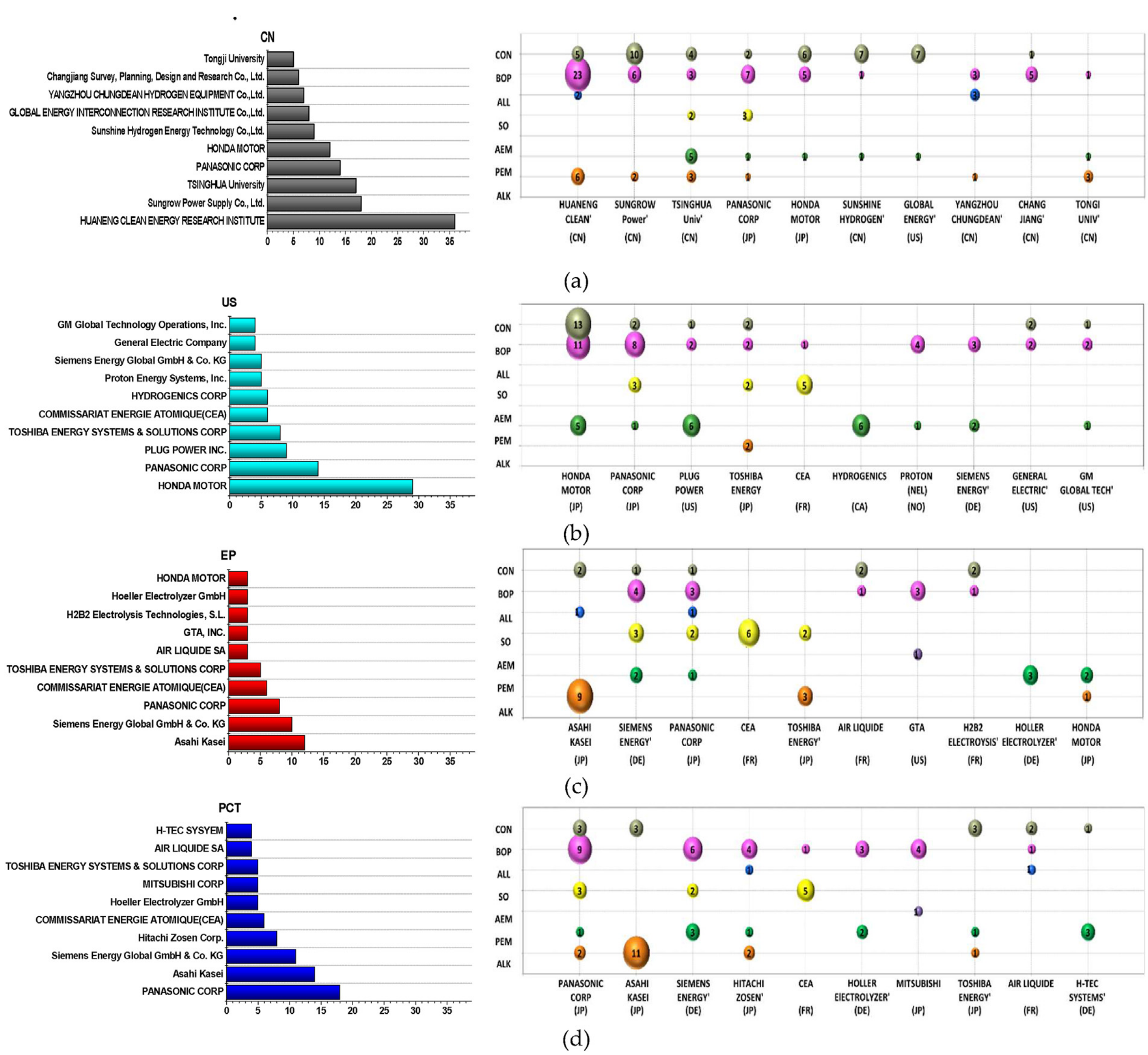


Fig. 5 – Patent trend by applicants: (a) China; (b) U.S.A; (c) Europe; (d) PCT

of green hydrogen field hence these countries are actively engaged in research and development of the green hydrogen industry. This trend can provide valuable insights for considering a future direction of potential markets as well as be able to make a strategy toward advancements in green hydrogen technology.

Patent trend by technology areas for major patent applicants

Top ten applicant companies in total number of patents are analyzed for technical areas of green hydrogen as shown in Fig. 6. Technology areas of water electrolysis will be described first of all. Japanese companies of Asahi Kasei, and Toshiba are leaders in technology area of Alkaline (ALK) as shown in Fig. 6(a). Next, German companies of Hoeller and Hydrogenics are advanced in development of PEM technology as shown in Fig. 6(b). In addition, Enapter, which merged into Italian company Acta SpA, is a leading inventor in AEM technology, followed by Mitsubishi as shown in Fig. 6(c). Lastly, Patent application on SO is led by a french company of Commissariat Energie Atomique (CEA), while companies including Panasonic corporation are also applied to the patents as shown in Fig. 6(d).

As of the system operation, Panasonic Corporation is a leading company in technology area of BOP, followed by Chinese company of Huaeng clean energy as shown in Fig. 6(e). From Fig. 6(f), technical area of control strategy (CON) is first advanced in Honda Motors and then company of Sungrow power supply, Asahi Kasei are following with the technology development on the water electrolysis in parallel. From these facts we can conclude that some of companies are heavily engaged in water electrolysis type, but some of global companies have invested both technology types.

Visualization of bibliometric network

In this section, network analysis is carried out to recognize the high-impact patents as a technical barrier in green hydrogen technologies. To realize this, a Python script is developed for pre-processing, and then VOSviewer software is analyzed to get relations between forward and backward patents. Network visualization is shown in Fig. 7, where patents are represented by a circle in Fig. 7(a), the size of which represents an impact level. And it is determined by weight for citation occurrences. More specifically, patent number in a middle of circle shows a patent number. The distance between any two patents indicates the similarity of the patents through co-citation links. In general, the closer the two patents are on the map, the stronger their relatedness is [43,44].

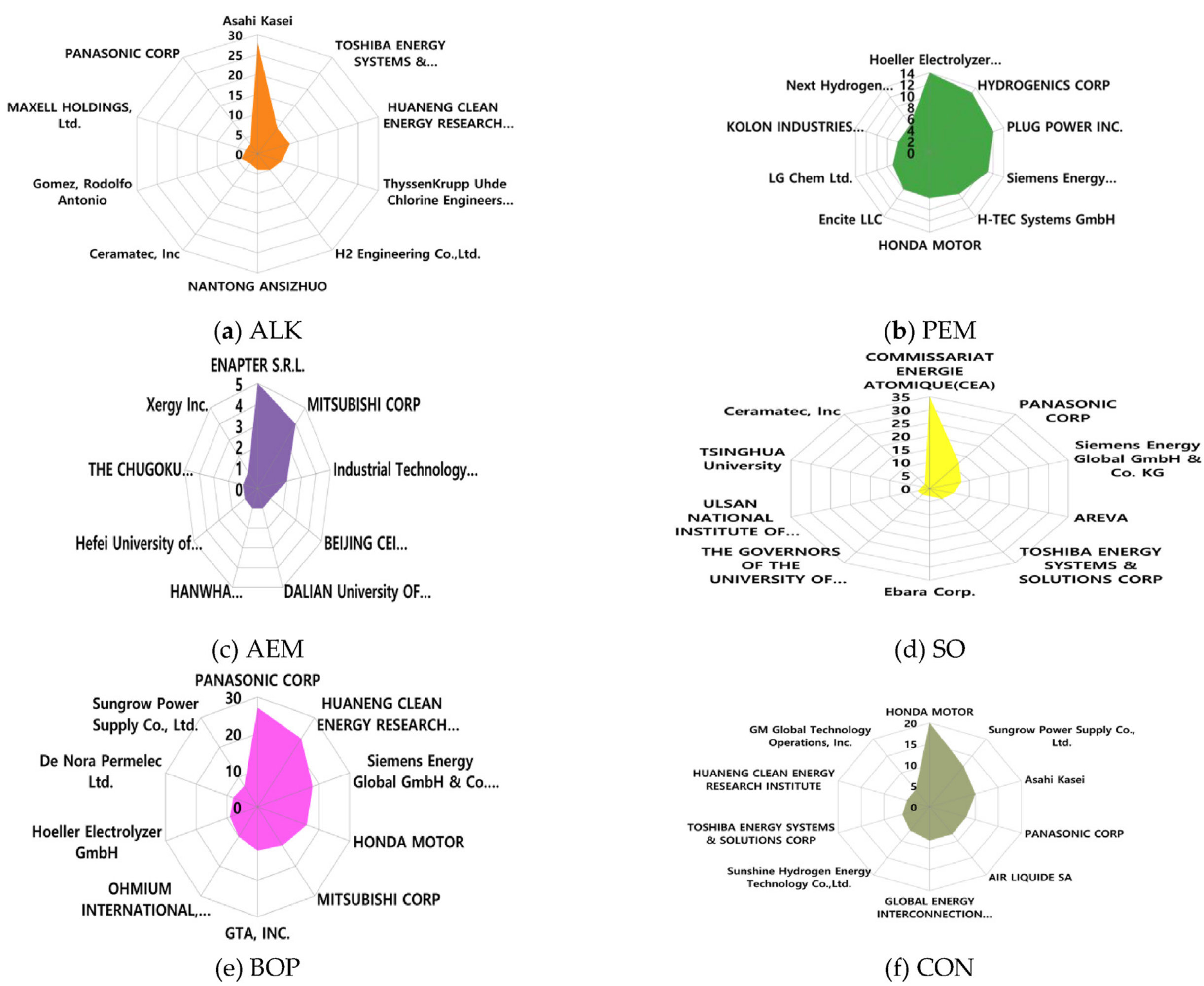
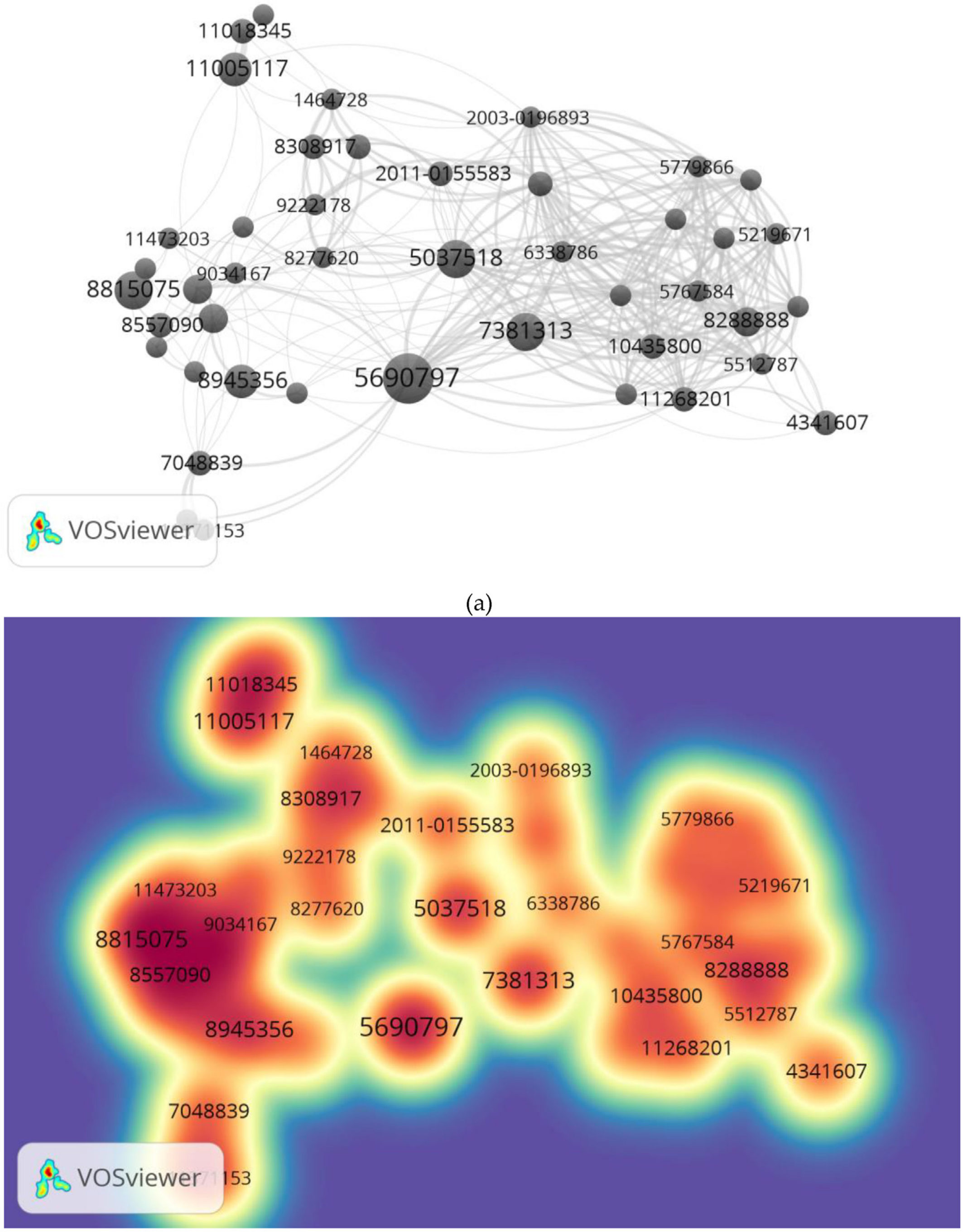


Fig. 6 – Innovation company by technical areas: (a) Alk; (b) PEM; (c) AEM; (d) SO; (e) BOP; (f) CON;



(a)

(b)

Fig. 7 — Network analysis visualization: (a) Co-citation network (b) density map visualization.

In our study, the valid patents account for a total of 1,305 as described in Table 6. According to the restriction of citation at least five occurrences, the circles in network visualization are only 44 patents among the 3,939 patents. Through the examination of an increased number of total patents, this is mainly caused by including patents before the year 2002, and some difference in the result may arise from the inaccurate choice of keywords in Appendix B. It has not yet been completely made clear because of insufficient data, whether the selection of keywords is dependent on experts by experience hence global patents in the green hydrogen field may not cover all. However, we have subsequently collected further data on global patents and wish to report the updated version later.

The map of patent density is visualized in Fig. 7(b). Each patent in the network of density maps has a color that indicates citation occurrences. We would like to introduce the two related patents below. For example, patent number 5690797 is about a hydrogen and oxygen gas generating system using water electrolysis in the year 1997. With a similar technical area, another patent number 5037518 is also about a gas generation of hydrogen and oxygen by electrolytic dissociation of water in the year 1989. Interestingly, both patents are not categorized as CPC standards but are classified as IPC standards with C25B*, which is surveyed the initial IPC code. We identified the most impactful patents during the past years using co-citation analysis. The excellent properties of this method are rapidly showing a correlation among a lot of patents in this field. However, it would be pivotal to discuss the limitation of co-citation analysis. The above two patents are more important than the others but that period of patent right is already expired over two decades. Since the results were obtained out of date, those are not the technical barrier despite high scores. We present that network analysis is not suitable for predicting live patents even though there is little correlation among patents of green hydrogen production.

High-impact patents

For the same reason, highly impactful patents are calculated by the suggested criteria, as introduced in Section Impact Index for Effective Patents. This is applied to all patents which are classified into seven technology areas of green hydrogen. Again, criteria for important patents are summed by forward relations, family patents, registration, and the remaining period of registration. The top high-impact patents for every seven technical areas are summarized in Table 7, where total points correspond to the summation of all scores. The resultant total score ranges from a minimum of 3.7 to a maximum of 4.3. A majority of high-impact patents have relatively a long period of remaining registration.

We would like to introduce representative patents of seven technology areas as below. For example, the patent number CN 2017–80008282, in a technical area of ALK, describes an apparatus for alkaline water electrolysis including gas-liquid separators for separating electrolytes and oxygen/hydrogen gas, and first and second electrolyte tanks for storing the separated electrolytes. Oxygen and hydrogen gas feed and exhaust pipes allow gas to flow in and out, and a circulator supplies the electrolytes to the electrolysis vessel. The patent number of US 13/623689, as of PEM, has a characteristic of a device for electrolyzing water, with an ion exchange structure separating the chamber into two compartments, and a reservoir in the high-pressure chamber to store water for electrolysis. In addition, the patent number EP 2016–857398 as AEM shows a hydrogen generator with an electrolytic cell separated by an Anion Exchange Membrane (AEM) into a cathode chamber and an anode chamber. Water is supplied to each chamber, and the cathode and anode receive power from respective feeders. The anode chamber also includes an active oxygen reduction material. The patent number of US 13/995305 as SO explains a hydrogen-producing cell consisting of a High-Temperature Steam Electrolyzer (HTSE) cell and an electrochemical pump cell. The HTSE cell has a porous cathode and anode, and the pump cell has a porous anode and cathode, both separated by dense, gases-impervious electrolytes. The patent number EP 2014–723004, as of ALL, describes a hydrogen gas generator system with a reactor stack for the electrolysis of water in an electrolyte solution, comprising spaced electrode plates and a separator to separate gas from the electrolyte solution. A pump circulates the electrolyte solution from the separator/reservoir through the reactor stack and back.

As seen in the system operation type, BOP and CON subtypes are discussed. The patent number CN 2009–80152767, as of BOP, has a system for distributing electrical power from a wind farm to multiple electrolyzer modules for hydrogen production. The system can distribute medium to high-voltage AC or medium-voltage DC electricity to the modules. The patent number KR 10-2012-7019134 shows a system for interconverting hydrogen and electrical energy, which

Table 7 – Highly impactful patents by the criterion of impact score (see section 2.3.3).

Technical Area	Patent Code	Registration	Duration of the Remaining Period of Registration	Number of Patents in Forward Relations	Countries for Family Patents	Total Score
ALK	US 16/965150	1	1.5	0.5	1	4
	CN 2017-80008282	1	1.5	0.5	1	4
	US 15/558861	1	1.5	0.5	0.8	3.8
PEM	US 13/623689	1	1.5	0.8	1	4.3
	EP 2018-726925	1	1.5	–	1.5	4
	US 14/785466	1	1.5	0.7	0.8	4
AEM	EP 2016-857398	1	1.5	0.5	0.8	3.8
	KR 10-2022-7003037	–	1.5	0.5	0.8	2.8
	KR 10-2020-0150363	–	1.5	0.5	0.5	2.5
SO	US 13/995305	1	1.4	0.7	1	4.1
	FR 2007-057821	1	1.2	0.8	1	4
	FR 2010-060840	1	1.4	0.5	1	3.9
ALL	EP 2014-723004	1	1.5	0.5	0.8	3.8
	CN 2013-10399761	1	1.5	0.5	0.7	3.7
	US 15/773365	1	1.5	0.5	0.7	3.7
BOP	CN 2009-80152767	1	1.3	0.5	1.2	4
	CN 2015-80026116	1	1.5	0.5	1	4
	US 15/526057	1	1.5	0.7	0.8	4
CON	KR 10-2012-7019134	1	1.4	0.5	1.2	4.1
	CN 2016-10835183	1	1.5	0.5	1	4
	CN 2006-80052901	1	1.2	0.5	1	3.7

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

includes a reversible conversion stage, a hydrogen pressure change stage, and an energy management and regulation stage.

Technology maturity in green hydrogen production

The technology life cycle model is a great metric to investigate a maturity in technology evolution throughout the four steps of technology development, maturity, recession, and resurrection [42,96,97]. This model is applied to the four commercial green hydrogen technologies of ALK, PEM, AEM and SO as shown in Fig. 8. The ratio between the number of patents and the number of applicants is represented by every five years. It is shown in Fig. 8 that all four technology areas have an increasing number of applicants and patents toward the technology maturity step. It can be seen that the technology areas of ALK and PEM are entering a stage of technology maturity, whereas the technology areas of AEM and SO are still at an early stage of technology development. It can be observed from the results shown in Fig. 8 (c) and (d) that technology development of AEM and SO is rapidly carried out. The technical maturity can be achieved through the amount of time and research by various institutions and there is a high chance that technologies related to ALK and PEM have already been much commercialized. Therefore, the technologies of AEM and SO may have lower technical barriers to the market entry and commercialization due to their early development stage. It should be noted that ALK type revealed significant mutual technology and PEM type has also about to be mutual technology as shown in Fig. 8 (a) and (b).

Technology entry barriers in green hydrogen

As a method of technology forecasting, technical entry barriers by technology areas of water electrolysis are described to determine the focus areas for future investment, and for the advancement of present technology areas. The number of applicants versus that of patents is shown in Fig. 9 on the x- and y-axis, respectively, for four commercial green hydrogen technologies during the entire survey period. In particular, the number of applicants and patents is higher than average, which is represented by vertical and horizontal centerlines in Fig. 9, in ALK and PEM technologies. However, SO and AEM show a relatively lower number than ALK and PEM both the

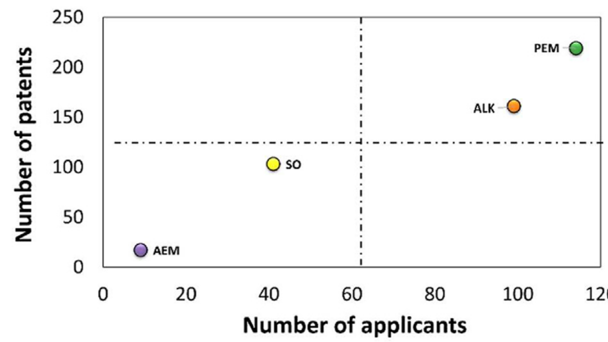


Fig. 9 – Applicants versus patents graph on four water electrolysis technologies.

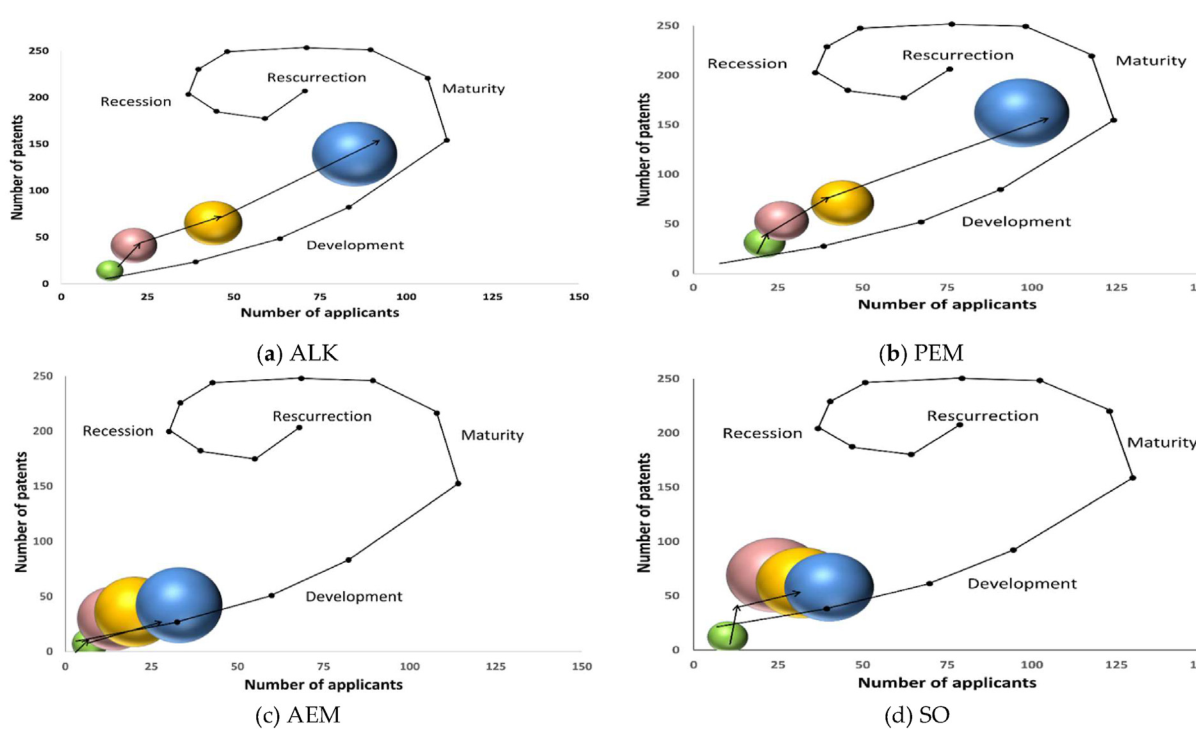


Fig. 8 – Technology maturity by technical areas of (a) ALK; (b) PEM; (c) AEM; (d) SO.

number of applicants and patents. Although the number of applicants and patents for SO is close to the average values, those for AEM are away from the average. This result reveals that AEM has a lower technology entry barrier than others. A recent report from IRENA predicts the similar trend technology areas of AEM and SO have high potential to be more active in technology development [38].

Conclusions

The present study contributes to a very timely discussion to predict the future trends of technologies within the market, especially focusing on green hydrogen production. From the wide range of literature surveys, green hydrogen technology was classified into two technology types: water electrolysis and system operation with a total of seven technical areas including, but not limited to: ALK, PEM, AEM, SO, ALL, BOP, and CON. Through the methods of both quantitative and qualitative searches, 5,471 patents data from the WIPS database were extracted and cleaned. And as of 1,305 valid patents related to green hydrogen production technologies over the past twenty years to analyze the patent database with high accuracy, especially noise filtering and web scraping methods. Valid patents were filtered using a combination of keywords and the IPC and CPC codes, and the developed method of the web scraping technique investigated the correlation of the patent data. With these classifications and the collected database, a novel flow chart for the analysis of green hydrogen production technology is suggested in this study.

Firstly, the results of the analysis presented the technology trend by years, technology types, countries, and applicants. As a result of the global patent trend in the past 20 years, the number of patents has had a consistent increase lately in the total number of patents. Overall, the technology areas of ALK and PEM constituted the total portion of 64%, of water electrolysis type. Besides, the technology type of system operation took up 53% and was more than the water electrolysis type. This fact has indicated that companies have recently invested in technology type of system operation including the technology area of BOP and CON, which can be proven practically by the dramatic increase in China. Further, we can also report on the result that China had about 40% of the total patents, followed by the PCT (WO) with 16%. Since China had a much higher potential market in green hydrogen production than other countries, the green hydrogen production technology was being developed mostly in countries of large economic size, with international patents in PCT. It is also interesting to observe the emerging SO area around 2011 in Europe, in which the traditional technologies have been further advanced and accompanied by fuel cell technology. Also, the top ten applicant companies were analyzed for the technical areas of green hydrogen as well as each country. The leading companies in the technology area of ALK are Asahi Kasei and Toshiba, while German companies Hoeller and Hydrogenics are advanced in the development of PEM. Enapter is a leading inventor in AEM technology, followed by Mitsubishi. The French company Commissariat Energie Atomique (CEA) leads in patent applications on SO technology, while Panasonic Corporation is the leading company in the technology area of BOP. In the technical area of control strategy (CON), Honda Motors is first in the being the most advanced, followed by Sungrow power supply and Asahi Kasei. Some companies were heavily engaged in the water electrolysis type, while some global companies have invested in both technology types.

Secondly, the major analysis techniques discussed in terms of the technology life cycle, visualization through network analysis, and high-impact patents. Four commercial technology areas of water electrolysis type are ALK, PEM, AEM, and SO and they have been analyzed to predict the near-term trends. It is considered the number of patents and applicants over a five-year period to determine the stage of technology development. The result shows that AEM and SO had lower technical barriers to market entry and commercialization due to their stages of early development. It should be also noted that ALK type revealed significant mutual technology and PEM type has also about to be mutual technology. As for technology energy barriers, the number of applicants and patents for the four commercial green hydrogen technologies were compared over the entire survey period. The number of applicants and patents shows that SO was close to the average values, while AEM had a lower number for both applicants and patents hence AEM had a lower technology entry barrier than others. These results can help determine the focus areas for future investment and the advancement of present technology areas.

The network analysis was utilized to understand high-impact patents as a technical barrier in green hydrogen technologies. A Python script was developed to identify forward and backward relations of a specific patent to others, which was cited by patents in the following years. The VOS-viewer software was analyzed to get the visualization of the co-citation network, and each patent in the network of density maps had a color that indicated citation occurrences. We could verify that the example of two patents was not the technical barrier despite high scores. All results of the patent analysis were demonstrated graphically for a better understanding of trends.

The high-impact patents for every seven technical areas were summarized, which ranged the result from a minimum of 3.7 to a maximum of 4.3. The criteria for important patents were summed by forward relations, family patents, registration, and the remaining period of registration. Representative patents of seven technology areas were introduced, such as the patent number CN 2017–80008282 in the technical area of ALK, which describes an apparatus for alkaline water electrolysis including gas-liquid separators for separating electrolytes and oxygen/hydrogen gas. Another example was patent number US 13/623689, as of PEM, which had a characteristic of a device for electrolyzing water, with an ion exchange structure separating the chamber into two compartments and a reservoir in the high-pressure chamber to store water for electrolysis. A majority of the high-impact patents had relatively a long period of remaining registration. From the facts described above, we can conclude that the method of high-impact patents would be a better option to recognize technical barriers because of affecting more criteria metrics than co-citation analysis.

Thirdly, it is pivotal to mention the limitations of this analysis with a limitation of access and lexicons. There might have been some unseen applicant companies that did not want to share their patent data hence the information of such companies was limiting access to the public. Next, there might have also been an inaccurate choice of keywords in search terms. It has not yet been completely made clear because of insufficient data, whether the selection of keywords were dependent on experts by experience. With IPC and CPC recently being updated, the accuracy of data would be increased by considering the details of classified codes. Furthermore, network analysis is not suitable for predicting live patents even though there is little correlation among the patents of green hydrogen production.

In future work, we have subsequently continued and collected further data on global patents and wish to report the updated version later. And we also would like to develop an AI-based algorithm to help easily analyze the relationship among important patents and orders of technology advancements.

Author contributions

"Methodology, Data Analysis, Writing, Donguk Yang; Investigation, Data Curation, Juhaeng Lee; Python coding, Nicholas Chaehoon Song; Resources, Sangseon Lee; Administration, Sangkyu Kim; Supervision, Sukho Lee.; Review and Editing, Seongim Choi.; All authors have read and agreed to the published version of the manuscript."

Funding

This research was supported by the KEPCO under the project entitled by "Development of gas concentration measurement technology and monitoring system for hydrogen facilities (No. R21XA06)". The authors wish to thank KEPCO for their financial support.

Data availability statement

Please refer to the suggested data in "WIPS Global" at http://www.wipsglobal.com/service/mai/main.wips. The web scraping python code is available at https://github.com/ray0717/Hydrogen_Patent_Analysis.

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.

Acknowledgments

We would like to thank AFORE 2022 Conference reviewers for their helpful advice on an earlier draft of this paper. We are also grateful to International Journal of Hydrogen Energy editors and anonymous reviewers for their comments during the critical reading of the manuscript. Above all, we give all the glory to God.

Appendix A, B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.04.317.

REFERENCES

[1] Bouckaert S, Pales AF, McGlade C, Remme U, Wanner B, Varro L, D'Ambrosio D, Spencer T. Net zero by 2050: a roadmap for the global energy sector. 2021. Available, https://iea.blob.core.windows.net/assets/063ae08a-7114-4b58-a34e-39db2112d0a2/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf. [Accessed 1 April 2023].

[2] Lee J, Lee J, Wi YM. Impact of revised time of use tariff on variable renewable energy curtailment on Jeju island. Electronics (Switzerland) Jan. 2021;10(2):1–20. https://doi.org/10.3390/electronics10020135.

[3] Sdanghi G, Maranzana G, Celzard A, Fierro V. Towards non-mechanical hybrid hydrogen compression for decentralized hydrogen facilities. Energies Jun. 2020;13(12). https://doi.org/10.3390/en13123145.

[4] Mao G, Han Y, Liu X, Crittenden J, Huang N, Ahmad UM. Technology status and trends of industrial wastewater treatment: a patent analysis. Chemosphere Feb. 2022;288. https://doi.org/10.1016/j.chemosphere.2021.132483.

[5] Li T, He X, Gao P. Analysis of offshore LNG storage and transportation technologies based on patent informatics," Cleaner engineering and technologyvol. 5. Elsevier Ltd; Dec. 01, 2021. https://doi.org/10.1016/j.clet.2021.100317.

[6] Ma SC, Xu JH, Fan Y. Characteristics and key trends of global electric vehicle technology development: a multi-method patent analysis. J Clean Prod Mar. 2022;338. https://doi.org/10.1016/j.jclepro.2022.130502.

[7] da Silveira F, Ruppenthal JE, Lermen FH, Machado FM, Amaral FG. Technologies used in agricultural machinery engines that contribute to the reduction of atmospheric emissions: a patent analysis in Brazil, vol. 64. World Patent Information; Mar. 2021. https://doi.org/10.1016/j.wpi.2021.102023.

[8] Sinigaglia T, Eduardo Santos Martins M, Cezar Mairesse Siluk J. Technological evolution of internal combustion engine vehicle: a patent data analysis. Appl Energy Jan. 2022;306. https://doi.org/10.1016/j.apenergy.2021.118003.

[9] Li X, Yuan X. Tracing the technology transfer of battery electric vehicles in China: a patent citation organization network analysis. Energy Jan. 2022;239. https://doi.org/10.1016/j.energy.2021.122265.

[10] Severo IA, dos Santos AM, Deprá MC, Barin JS, Jacob-Lopes E. Microalgae photobioreactors integrated into combustion processes: a patent-based analysis to map technological trends. Algal research, vol. 60. Elsevier B.V.; Dec. 01, 2021. https://doi.org/10.1016/j.algal.2021.102529.

[11] Lee M. An analysis of the effects of artificial intelligence on electric vehicle technology innovation using patent data. World Patent Inf Dec. 2020;63. https://doi.org/10.1016/j.wpi.2020.102002.

[12] Yuan X, Li X. Mapping the technology diffusion of battery electric vehicle based on patent analysis: a perspective of global innovation systems. Energy May 2021;222. https://doi.org/10.1016/j.energy.2021.119897.

[13] Suh JW, Sohn SY, Lee BK. Patent clustering and network analyses to explore nuclear waste management

technologies. Energy Pol Nov. 2020;146. https://doi.org/10.1016/j.enpol.2020.111794.

[14] Yin C, Gu H, Zhang S. Measuring technological collaborations on carbon capture and storage based on patents: a social network analysis approach. J Clean Prod Nov. 2020;274. https://doi.org/10.1016/j.jclepro.2020.122867.

[15] Leng Z, Sun H, Cheng J, Wang H, Yao Z. China's rare earth industry technological innovation structure and driving factors: a social network analysis based on patents. Resour Pol Oct. 2021;73. https://doi.org/10.1016/j.resourpol.2021.102233.

[16] Spreafico C, Russo D, Spreafico M. Investigating the evolution of pyrolysis technologies through bibliometric analysis of patents and papers. J Anal Appl Pyrolysis Oct. 2021;159. https://doi.org/10.1016/j.jaap.2021.105021.

[17] Chanchetti LF, Oviedo Diaz SM, Milanez DH, Leiva DR, de Faria LIL, Ishikawa TT. Technological forecasting of hydrogen storage materials using patent indicators. Int J Hydrogen Energy Nov. 2016;41(41):18301–10. https://doi.org/10.1016/j.ijhydene.2016.08.137.

[18] Noh Soon-Young, et al. Technology characteristics of hydrogen storage and its technology trend by the patent analysis. Transactions of the Korean hydrogen and new energy society Feb. 2008;19(1):90–102. Available : https://koreascience.kr/ksci/search/article/articleView.ksci?articleBean.atclMgntNo=SSONB2_2008_v19n1_90. [Accessed 1 April 2023].

[19] Rizzi F, Annunziata E, Liberati G, Frey M. Technological trajectories in the automotive industry: are hydrogen technologies still a possibility? J Clean Prod Mar. 2014;66:328–36. https://doi.org/10.1016/j.jclepro.2013.11.069.

[20] Sinigaglia T, Freitag TE, Kreimeier F, Martins MES. Use of patents as a tool to map the technological development involving the hydrogen economy, vol. 56. World Patent Information; Mar. 2019. p. 1–8. https://doi.org/10.1016/j.wpi.2018.09.002.

[21] Choi H, Woo JR. Investigating emerging hydrogen technology topics and comparing national level technological focus: patent analysis using a structural topic model. Appl Energy May 2022;313. https://doi.org/10.1016/j.apenergy.2022.118898.

[22] Baumann M, et al. Comparative patent analysis for the identification of global research trends for the case of battery storage, hydrogen and bioenergy. Technol Forecast Soc Change Apr. 2021;165. https://doi.org/10.1016/j.techfore.2020.120505.

[23] Yang H, et al. Exploring future promising technologies in hydrogen fuel cell transportation. Sustainability Jan. 2022;14(2). https://doi.org/10.3390/su14020917.

[24] Chen YH, Chen CY, Lee SC. Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies. Int J Hydrogen Energy Jun. 2011;36(12):6957–69. https://doi.org/10.1016/j.ijhydene.2011.03.063.

[25] Hwang GJ, Kang KS, Han HJ, Kim JW. Technology trend for water electrolysis hydrogen production by the patent analysis. Trans. Of the Korean Hydrogen and New Energy Society Mar. 2007;18(No.1):95–108. Available, https://koreascience.kr/article/JAKO200721036737392.page. [Accessed 1 April 2023].

[26] Lai WH, Chen HY, Chang FY, Wu CC, Lin CY, Huang SR. Market and patent analysis of commercializing biohydrogen technology. Int J Hydrogen Energy Oct. 2011;36(21):14049–58. https://doi.org/10.1016/j.ijhydene.2011.03.155.

[27] Hsu CW, Chang PL, Hsiung CM, Lin CY. Commercial application scenario using patent analysis: fermentative hydrogen production from biomass. Int J Hydrogen Energy Nov. 2014;39(33):19277–84. https://doi.org/10.1016/j.ijhydene.2014.05.100.

[28] Hsu CW, Chang PL, Hsiung CM, Wu CC. Charting the evolution of biohydrogen production technology through a patent analysis. Biomass Bioenergy May 2015;76:1–10. https://doi.org/10.1016/j.biombioe.2015.02.035.

[29] Hsu CW, Lin CY. Using social network analysis to examine the technological evolution of fermentative hydrogen production from biomass. Int J Hydrogen Energy Dec. 2016;41(46):21573–82. https://doi.org/10.1016/j.ijhydene.2016.07.157.

[30] Olivo C, Lebedeva I, Chu CY, Lin CY, Wu SY. A patent analysis on advanced biohydrogen technology development and commercialisation: scope and competitiveness. Int J Hydrogen Energy Oct. 2011;36(21):14103–10. https://doi.org/10.1016/j.ijhydene.2011.04.100.

[31] Martinez-Burgos WJ, et al. Hydrogen: current advances and patented technologies of its renewable production" Journal of cleaner productionvol. 286. Elsevier Ltd; Mar. 01, 2021. https://doi.org/10.1016/j.jclepro.2020.124970.

[32] Ampah JD, et al. Investigating the evolutionary trends and key enablers of hydrogen production technologies: a patent-life cycle and econometric analysis. Int J Hydrogen Energy 2022. https://doi.org/10.1016/j.ijhydene.2022.07.258.

[33] Abbas A, Zhang L, Khan SU. A literature review on the state-of-the-art in patent analysis," World patent informationvol. 37. Elsevier Ltd; 2014. p. 3–13. https://doi.org/10.1016/j.wpi.2013.12.006.

[34] Trappey A, Trappey Cv, Hsieh A. An intelligent patent recommender adopting machine learning approach for natural language processing: a case study for smart machinery technology mining. Technol Forecast Soc Change Mar. 2021;164. https://doi.org/10.1016/j.techfore.2020.120511.

[35] Souili A, Cavallucci D, Rousselot F. Natural Language Processing (NLP) - a solution for knowledge extraction from patent unstructured data. Procedia Eng 2015;131:635–43. https://doi.org/10.1016/j.proeng.2015.12.457.

[36] Madani F, Weber C. The evolution of patent mining: applying bibliometrics analysis and keyword network analysis, vol. 46. World Patent Information; Sep. 2016. p. 32–48. https://doi.org/10.1016/j.wpi.2016.05.008.

[37] Mendonça AKDS, Vaz CR, Lezana ÁGR, Anacleto CA, Paladini EP. Comparing patent and scientific literature in airborne wind energy. Sustainability 2017;9:6. https://doi.org/10.3390/su9060915. MDPI.

[38] Taibi E, et al. Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5ºC climate goal [Online]. International Renewable Energy Agency(IRENA); 2020. Available: www.irena.org/publications. [Accessed 1 April 2023].

[39] WIPS global website, Available : https://www.wipsglobal.com/service/mai/main.wips; [accessed on 1 April 2023].

[40] IPC classification codes, Available : https://www.wipo.int/classifications/ipc/en/; [accessed on 1 April 2023].

[41] CPC classification codes, Available : https://www.cooperativepatentclassification.org/index; [accessed on 1 April 2023].

[42] Patent map using patent information. KIPO and KIPI 2015. Available: https://lib.snu.ac.kr/sites/default/files/2015_hangugteugheojeongboweon_teugheojeongbo_hwalyong_teugheomaeb_gyojae_v3.pdf. [Accessed 1 April 2023].

[43] Van Eck, Jan Ness, Waltman Ludo. VOSviewer manual: manual for VOSviewer. Version 1.6.18. Jan. 2022. Available : https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.18.pdf. [Accessed 1 April 2023].

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

[44] van Eck NJ, Waltman L, Dekker R, van den Berg J. A comparison of two techniques for bibliometric mapping: multidimensional scaling and VOS. J Am Soc Inf Sci Technol 2010;61(12):2405–2416, Dec. https://doi.org/10.1002/asi.21421.
[45] WIPS website, Available : https://www.wipo.int/pct/en/pct_contracting_states.html; [accessed on 1 April 2023].
[46] Widera B. Renewable hydrogen as an energy storage solution," in E3S web of conferencesvol. 116; Sep. 2019. https://doi.org/10.1051/e3sconf/201911600097.
[47] Eneco and OCI join NorthH2 offshore wind-to-hydrogen consortium. Mar. 2022. Available : https://www.offshore-energy.biz/eneco-and-oci-join-north2-offshore-wind-to-hydrogen-consortium/. [Accessed 1 May 2022].
[48] PosHYdon. First green offshore hydrogen pilot explained. Oct. 2019. Available : https://www.offshorewind.biz/2019/10/23/poshydon-first-green-offshore-hydrogen-pilot-explained-video/. [Accessed 1 April 2023] [accessed on.
[49] The hydrogen chain step 2 : the Energy Observer electrolyser. Sep. 2022. Available : https://www.energy-observer.org/resources/hydrogen-chain-electrolyser/. [Accessed 1 April 2023].
[50] ERM. The business of sustainability ERM dolphyn hydrogen phase 2-final report comprising: detailed design for 2MW scale prototype pre-FEED for 10MW commercial scale demonstrator public report. 2021. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051827/Phase_2_Report_-_ERM_-_Dolphyn.pdf. [Accessed 1 April 2023].
[51] H2ARVESTER website. Available: https://www.h2arvester.nl/?lang=en/; [accessed on 1 April 2023].
[52] HYGRO enabling hydrogen from wind to wheel", Challenges for the energy transition I: power supply & System integration in 2050 'WindDays'. Jun 2018. . [Accessed 1 May 2022].
[53] SHyLO to trial hydrogen storage solution at EMEC's H2 platform. Available, https://www.offshore-energy.biz/shylo-to-trial-hydrogen-storage-solution-at-emecs-h2-platform. [Accessed 24 May 2022].
[54] HORIZON POWER website. Available: https://renewtheregions.com.au/projects/denham-hydrogen-demonstration-plant/; [accessed on Sep 2022].
[55] Harrison KW, et al. The wind-to-hydrogen project: operational experience, performance testing, and systems integration. 2009 [Online]. Available: https://www.nrel.gov/docs/fy09osti/44082.pdf;. [Accessed 1 May 2022].
[56] Widera B. Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. Therm Sci Eng Prog May 2020;16. https://doi.org/10.1016/j.tsep.2019.100460.
[57] Yamane F. Fukushima hydrogen energy research field (FH2R)," Toshiba. 29 Oct 2019. Available : https://www.nedo.go.jp/content/100899755.pdf. [Accessed 1 April 2023].
[58] Australian Gas Infrastructure Group website. Available: https://www.agig.com.au/hydrogen-park-south-australia/; [accessed on Sep. 2022].
[59] Clean manufacturing in Saerbeck. Available, https://www.enapter.com/newsroom/clean-manufacturing-in-saerbeck/. [Accessed 7 February 2022].
[60] Power your life with LAVO. Available, https://www.h2networks.com.au/pdf/Small-Scale-LAVO-Residential-Unit-Brochure.pdf/. [Accessed 1 May 2022].
[61] Ulsan Techno Industrial Complex, KEPCO Electric Power Research Institute launched 'P2G-based KEPCO MG demonstration project'. Available: http://www.epj.co.kr/news/articleView.html?idxno=24297/; [accessed on Sep 2022].
[62] Freymann J, et al. "Deliverable Report Title: assessment of hydrogen certification standards and requirements". Sunfire; 9 Nov 2020.
[63] Isles J, Jaeger H. "Accelerating the technology roadmap for decarbonizing gas turbines via hydrogen fuel". Gas Turbine World; Dec 2020.
[64] Pioneering 10-MW baseload hydrogen power plant breaks ground in French guiana. Available, https://www.powermag.com/pioneering-10-mw-baseload-hydrogen-power-plant-breaks-ground-in-french-guiana/. [Accessed 1 April 2023].
[65] Savastano M. Renewable hydrogen: the key enabler for a zero carbon transition. the 2nd hydrogen energy ministerial meeting 25 Sep 2019. Available : https://www.nedo.go.jp/content/100920880.pdf. [Accessed 1 April 2023].
[66] Power to green hydrogen mallorca starts construction of the photovoltaic plant in lloseta. 3 Aug 2021. Available: https://www.enagas.es/en/press-room/news-room/press-releases/03_08_2021_NP_Inicio_obras_planta_Lloseta_Power_to_Green_H2_Mallorca/. [Accessed 1 April 2023].
[67] Slater S, et al. D7.2 Brief summary report on initial policy implications of the bulk electrolyser model for FCHJU Version control. SINTEF; Oct 2020. Available : https://refhyne.eu/wp-content/uploads/2021/11/D7.2-report-v7.0-clean.pdf. [Accessed 1 April 2023].
[68] Riveros-Godoy G, Rivarolo M, Massardo AF, Arevalos G. Lean H2 and NH3 large production in Paraguay by the 14 GW Itaipu hydroelectric facility," in E3S web of conferencesvol. 113; Aug. 2019. https://doi.org/10.1051/e3sconf/201911301009.
[69] Mitsubishi Power builds hydrogen park to test next-gen technologies. Available, https://www.powerengineeringint.com/hydrogen/mitsubishi-power-builds-hydrogen-park-to-test-next-gen-technologies/. [Accessed 1 April 2023].
[70] Energie Park MAINZ website. Available, https://www.energiepark-mainz.de/en/project/energiepark/. [Accessed 1 April 2023].
[71] "Eyre peninsula electricity grid upgrade solution.". Energy Security for South Australia Working Party(ESSAWP); 2017. Available : https://www.electranet.com.au/wp-content/uploads/ritt/2017/04/ESSAWP.pdf. [Accessed 1 April 2023].
[72] Clean manufacturing in saerbeck. Available, https://www.enapter.com/newsroom/clean-manufacturing-in-saerbeck/. [Accessed 1 April 2023].
[73] Jeju Dongbok·Bukchon wind power plant water electrolysis large-scale demonstration. 20 Apr 2022. Available: https://www.e2news.com/news/articleView.html?idxno=241359/ [accessed on Sep 2022].
[74] Raschilla S. Environmental referral supporting document murchison hydrogen renewables project. The Power of Commitment 2022. Available, https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Murchison%20Hydrogen%20Renewables%20-%20Environmental%20Referral%20Supporting%20Document_Rev2.pdf [accessed on Sep 2022].
[75] SALCOS Website. Available: https://salcos.salzgitter-ag.com/en/windh2.html/; [accessed on 1 April 2023].
[76] Gigastack phase 2: pioneering UK renewable hydrogen public report. Mar 2021. Available : https://gigastack.co.uk/content/uploads/2021/11/Gigastack-Phase-2-Public-Report_FINAL_.pdf. [Accessed 1 April 2023].
[77] Parker P. HT1 hydrogen demonstrator project EIA screening opinion request report 80925. VATTENFALL; Nov 2021. Available : https://marine.gov.scot/sites/default/files/vattenfall_-_screening_opinion_request_report_redacted.pdf. [Accessed 1 April 2023].

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317

[78] Christmas creek renewable hydrogen mobility project. Available, https://research.csiro.au/hyresource/christmas-creek-renewable-hydrogen-mobility-project/. [Accessed 1 April 2023].
[79] Yara, Engie. ENGIE-YARA renewable hydrogen and ammonia deployment in pilbara YURI phase 0: feasibility study knowledge sharing report. Oct 2020. Available : https://arena.gov.au/assets/2020/11/engie-yara-renewable-hydrogen-and-ammonia-deployment-in-pilbara.pdf. [Accessed 1 April 2023].
[80] Jupiter 1000 : Démonstrateur industriel de Power-to-Gas. GRTgaz; 2022. Available : https://www.jupiter1000.eu/_files/ugd/940962_37b45cebbbe842c6b3eaad4b6dcaaea2.pdf. [Accessed 1 April 2023].
[81] Atco | clean energy innovation HUB lessons. ARENA INSIGHTS FORUM; Nov 2019. Available : https://arena.gov.au/assets/2019/12/atco-clean-energy-innovation-hub-lessions.pdf. [Accessed 1 April 2023].
[82] Maria E, Verbund P, Gbmh S. H2FUTURE Hydrogen meeting future needs of low carbon manufacturing value chains Programme Review Days 2018". 2018. Available: https://h2future-project.eu/. [Accessed 1 April 2023].
[83] Gerin G. "Deliverable 7.5 : final technical performance report". Air Liquide Jun 2021 [accessed on Sep 2022].
[84] E. Henning, "Session 01.B.04 the role of distribution infrastructure", Madrid Forum; [accessed on Sep 2022].
[85] World's largest green hydrogen project in China. 3 Feb 2022. Available: https://www.maritimegateway.com/worlds-largest-green-hydrogen-project-in-china/. [Accessed 1 April 2023].
[86] Abdelghany MB, et al. Deliverable D6.4 : public Control system for fuel-production use case. SINTEF; 5 Feb 2021. Available : https://www.haeolus.eu/wp-content/uploads/2020/08/D6.2.pdf. [Accessed 1 April 2023].
[87] Full-scale operations begin for showcase project to supply wind power-generated, low-carbon hydrogen to fuel cell forklifts. 2017. Available: https://global.toyota/en/detail/17737009/. [Accessed 1 April 2023].
[88] Power to gas" demonstration to start in hokkaido. 29 Sep 2017. Available: https://www.nedo.go.jp/english/news/AA5en_100291.html/ [accessed on Sep 2022].
[89] Zhao T, Liu H, Roeder K, Lafferty, Wasserman J. Terms and conditions Privacy policy the huge package for high-dimensional undirected graph estimation in R. 2012. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84860650411&partnerID=40&md5=1844dec5b49b3f6766be6b0a3b85b66/ [accessed on Sep 2022].
[90] Finding patent information: Derwent Innovations Index, University of Bath, Available: https://library.bath.ac.uk/patents/DII/; [accessed on 1 April 2023].
[91] Yang D, et al. "Technological analysis and forecasting of green hydrogen technology". AFORE 2022 28 Sep 2022:210. Available : https://drive.google.com/file/d/1km-bk9wvUZNVc2ejDDc4FRytKeDwcOi3/view/. [Accessed 1 April 2023].
[92] Yang D, et al. "Recent data analysis techniques for producing the green hydrogen". The conference of KIEE; 2 Nov 2022.
[93] Hosseini Seyed Ehsan. Transition away from fossil fuels toward renewables: lessons from Russia-Ukraine crisis. Future Energy May 2022;1(No. 1):2–5. https://doi.org/10.55670/fpll.fuen.1.1.8.
[94] Owusu Phebe Asantewaa, Asumadu-Sarkodie Samuel. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Engineering 3 Mar 2016;1:1167990. https://doi.org/10.1080/23311916.2016.1167990. Available : . [Accessed 1 April 2023].
[95] Hosseini Seyed Ehsan. Hydrogen has found its way to become the fuel of the future. Future Energy Nov 2022;1(3):11–2. Available : https://fupubco.com/fuen/article/view/28. [Accessed 1 April 2023].
[96] KIPSA. The investigation report of patent technology trend, 『Lightning observation Equipment』. Dec 2014. Available: https://scienceon.kisti.re.kr/srch/selectPORSrchReport.do?cn=TRKO201500008314. [Accessed 1 April 2023].
[97] KIPSA. The investigation report of patent technology trend, 『Meteorological equipment verification technology』. Dec 2014. Available: https://scienceon.kisti.re.kr/srch/selectPORSrchReport.do?cn=TRKO201500008313&dbt=TRKO. [Accessed 1 April 2023].
[98] Bayem H, Capely L, Dufourd F, Petit M. Probabilistic study of the maximum penetration rate of renewable energy in an island network. Bucharest, Romania, 2009: IEEE Bucharest PowerTech; 2009. p. 1–5. https://doi.org/10.1109/PTC.2009.5282158.
[99] Godula-Jopek Agata. Hydrogen production: by electrolysis. John Wiley & Sons; 2015.
[100] Parks K, Wan YH, Wiener G, Liu Y. "Wind energy forecasting: a collaboration of the national center for atmospheric research (NCAR) and Xcel energy." United States: N. 2011. https://doi.org/10.2172/1027161.

Please cite this article as: Yang D et al., Patent analysis on green hydrogen technology for future promising technologies, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.317