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Review article

Recent progress in electrolyser control technologies for hydrogen energy production: A patent landscape analysis and technology updates

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ABSTRACT

Alternative low-to-zero carbon technologies must be developed to facilitate the clean energy transition rather than only concentrating on one or a few specific technology trajectories. The hydrogen electrolyser has many benefits over traditional energy storage technologies, making it a competitive alternative to the current fossil fuel combustion-based energy generation system. To better understand the impact and developments of electrolyser control technologies for hydrogen production, this study aims to shed light on current research and patent trends. The research was conducted by performing extensive keyword searches on electrolyser control methods for hydrogen generation in the Lens database and then extracting the bibliometric data from the 107 patent publications selected based on keywords, family filtering and material exclusion. An up-to-date technical overview is provided with a bibliographic study of patent growth, key players and innovators, patent distribution across jurisdictions and technological sectors, and patent categorization using the cooperative patent classification (CPC) code. Key owners, inventors, and jurisdictional hierarchies in patent publications are also identified, and the potential for further study is assessed. These selected patent documents and their landscape analysis aim to provide a systematic foundation for future developments in electrolyser technologies and materials related to hydrogen production and to propose emerging research and commercialization prospects for future researchers.

1. Introduction

Hydrogen, one of earth's most common elements, is a highly adaptable energy source with uses in transportation (cars, trains, and planes), industry (making steel and ammonia), and more [1]. Burning hydrogen produces no harmful consequences like those from burning other fossil fuels [2]. For this reason, it is vital to investigate hydrogen technology further since it seems to be the most viable approach to dramatically reduce emissions [3]. The hydrogen economy has faced difficulties despite Hydrogen's more than two decades of recognition as a viable green fuel [4]. Foremost among these is discovering eco-friendly hydrogen production methods [5]. The world is working on a variety of eco-friendly technical solutions to meet the growing need for energy in transportation and other uses. Renewable energy (RE), biofuels, and hydrogen are all examples of such technology [6]. Rising pollution and greenhouse gas emissions, rapidly depleting liquid fuel supplies, and the need to get more use out of nonrenewable fossil fuels like coal and natural gas all point to the urgent need for innovative approaches to energy production [7].

Hydrogen has various benefits over other energy sources and is thus an excellent energy currency, transport, and storage medium [8]. At the point of consumption, it undergoes oxidation, resulting in producing zero waste in the form of pollutants, particulate matter, or greenhouse gases. In an internal combustion engine, combining hydrogen with another fuel like compressed natural gas (CNG), liquefied petroleum gas (LPG), or diesel may increase efficiency and decrease emissions of pollutants, particulate matter as well as hazardously high levels of nitrogen oxide (NOx) and carbon dioxide [9–12]. For mobile applications, hydrogen oxidized in fuel cells provides extremely high fuel-conversion efficiency (40–45 %), whereas for stationary applications, the entire

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system efficiency may reach 80–90 % with heat recovery [13]. Specifically, hydrogen's ability to store energy for infinitely long durations makes it useful for load levelling or compensating for fluctuations in supply and/or demand that occur anywhere from every hour to every season [14]. Today, more than 95 % of all hydrogen comes from non-renewable sources, mostly steam methane reformation, which uses fossil fuels as a heat source and releases carbon dioxide as a byproduct [15,16]. Hydrogen may be compressed to high pressures and utilized as a transportation fuel [17]. Although hydrogen-powered cars have received greater attention lately, the technology has been developing for decades [18]. There has been extensive R & D effort put towards hydrogen-powered automobile technology, as shown by the published patent literature and scientific literature [19,20]. The development of hydrogen and electric vehicles has been driven by the need to lessen the environmental impact of the transportation industry [21–23]. Pollutant emissions from these cars should be compared to those from vehicles powered by internal combustion engines so that a complete strategy may be developed to curb pollution from transportation in the future [24–26]. While driving a hydrogen car produces no emissions, the production technique of hydrogen might lead to more significant life cycle emissions than those of internal combustion vehicles [27,28]. Construction of an infrastructure is a fundamental difficulty that has to be addressed before hydrogen fuel cell cars can effectively address environmental and oil dependence issues in transportation [29,30]. Along with its promising potential in fuel cell vehicles, hydrogen provides promise for decarbonization initiatives in a variety of applications. Hydrogen can play an essential part in achieving low-carbon and sustainable solutions beyond the limits of transportation. In power generation, hydrogen can be utilized in fuel cells and combustion turbines to generate electricity with low emissions [31]. It can be used as a pure fuel source or feedstock in industrial processes such as manufacturing and refining, thus lowering greenhouse gas emissions [32]. Hydrogen also has applications in heating and cooling systems, where it can be used for space heating, water heating, and air conditioning to provide environmentally favorable alternatives. In addition, hydrogen works as an energy storage system, allowing for the integration of renewable energy sources and facilitating a more flexible and reliable energy system. Hydrogen can considerably contribute to the decarbonization of our energy landscape and pave the way for a sustainable future by investigating and exploiting these diverse application possibilities [31].

A wide range of techniques exist for hydrogen production including Steam Methane Reforming, Electrolysis, Partial Oxidation of Natural Gas, Biomass Gasification, Photoelectrochemical, Thermochemical Water Splitting [31–35]. Each of these techniques has its own advantages and disadvantages, and their suitability depends on various factors such as the availability of feedstock, cost, efficiency, and environmental impact [36–39]. One prominent technique is steam methane reformation, which not only converts natural gas into hydrogen but also generates [40,41]. Hydrogen production by electrolysis is a well-established, clean, and efficient technique, but it also comes at a high price [42–44]. Hydrogen is produced at high purity by a process called water electrolysis, which uses only electrical energy to separate water molecules into hydrogen and oxygen [45–48]. The Polymer Electrolyte Membrane (PEM) electrolyser is becoming more used as a device for water electrolysis [49–51]. Electrolyser may be useful tools in the quest to accomplish climate change goals by integrating several forms of renewable energy into the existing power infrastructure [52–54]. To generate hydrogen gas during times of abundant renewable infeed, a common and practical practice would be combining an electrolyser with a variable source of renewable energy, such as a photovoltaic (PV) array or wind turbine [55,56]. Electrolysis of water is an electrochemical process that generates hydrogen and oxygen when a voltage is applied to a solution of water [57]. In electrolysis, hydrogen and oxygen are extracted from water using an electrical current [58–60]. Electrical energy is used to break apart water molecules into their component gases, hydrogen, and oxygen [61–63]. Water in a PEM electrolyser is separated into protons and electrons by passing over a membrane [64]. Electric current delivered to the electrodes, which are separated by a membrane, cause water to split into hydrogen and oxygen [65,66]. As oxygen gas is created at the anode, hydrogen gas is collected at the cathode [67,68]. As compared to other technologies, electrolysis for creating hydrogen offers various benefits [69,70]. The readily accessible hydrogen in water may be harnessed by the device [71–73]. Also, it may be run on sustainable energy sources like wind or solar power, lowering the amount of greenhouse gases released into the atmosphere [74–77]. In contrast to other techniques of creating hydrogen, electrolysis may be less efficient and more costly due to the high energy requirements involved [78–80]. Alkaline water electrolysis (ALK) electrolyser [81], polymer electrolyte membrane water electrolysis (PEM) electrolyser [82], anion exchange membrane water electrolysis (AEM) electrolyser [83], and solid oxide fuel cell (SOFC) electrolyser [84] are just a few examples of the various varieties of water electrolysis cells available [70,73,80,85]. Given their high efficiency, low emissions, low noise, and fuel flexibility, solid oxide fuel cell (SOFC) systems have become more prevalent in stationary power production, mobile equipment power supply, and military equipment [86–88]. The limitations of solid oxide electrolyzers (SOECs) make them unsuitable for mobile applications. Their high operating temperatures and prolonged start-up times pose difficulties in terms of efficiency and portability [86]. Additionally, SOECs are less adaptable to load fluctuations since their optimal performance is dependent on stable and consistent operating conditions [87,88]. Alternative electrolyzer technologies, such as PEM electrolyzers, are more suitable for mobile applications due to their lower operating temperatures, quicker start-ups, and enhanced response to load fluctuations [89]. When selecting the proper electrolyzer technology for a given application, it is crucial to consider the application's unique requirements and constraints. When it comes to using renewable energy to produce hydrogen, PEM water electrolyser are among the most promising technologies [89,90,110]. PEM are predicted to be a potential alternative to the standard alkaline water electrolyser in low-temperature applications despite their shorter technical maturity (simplicity, greater current densities, solid electrolyte, higher working pressures) [91–94,110]. Recent outstanding advancements show PEM technology's potential [95]. Their primary benefits for coupling with renewable sources are 1) the elimination of potentially dangerous liquid electrolytes and the corresponding auxiliaries for electrolyte recirculation and control, 2) the ability to achieve faster dynamic response (easier start-up) due to the availability of higher current densities, and 3) the possibility of more compact designs [96–99]. Compared to other forms of electrolysis, PEM electrolysis is more effective [100]. Due to the PEM membrane's selective permeability to protons, the energy needed to create hydrogen may be significantly reduced [102]. As PEM electrolysis may begin and end operation rapidly, it is well suited for usage with variable renewable energy sources like wind and sun [103]. PEM electrolysis devices are perfect for distributed hydrogen generation since they are small and can be simply incorporated into existing infrastructure [104]. PEM electrolysis produces hydrogen with a purity of over 99.999 %, making it ideal for use in fuel cells [105]. Systems that use PEM electrolysis are reliable and may run for extended periods of time without requiring much upkeep [106]. As compared to other methods of hydrogen production, PEM electrolysis is safer since it does not need the use of high-pressure storage or gases that might easily catch fire [107]. Although the hydrogen production technology required to produce hydrogen by alkaline water electrolysis is quite costly, it is also one of the most straightforward approaches [105]. On-site electrolysis of water may be more cost-effective than other technologies if only modest amounts of hydrogen are needed [106]. Furthermore, electrolyser may serve as industrial loads that can be managed to take advantage of variable power pricing schemes like time-of-use [107]. Fig. 1 shows the hydrogen production process using electrolyser from renewable energy sources with wide range of its application.

Emerging electrolyzer technologies for the production of hydrogen

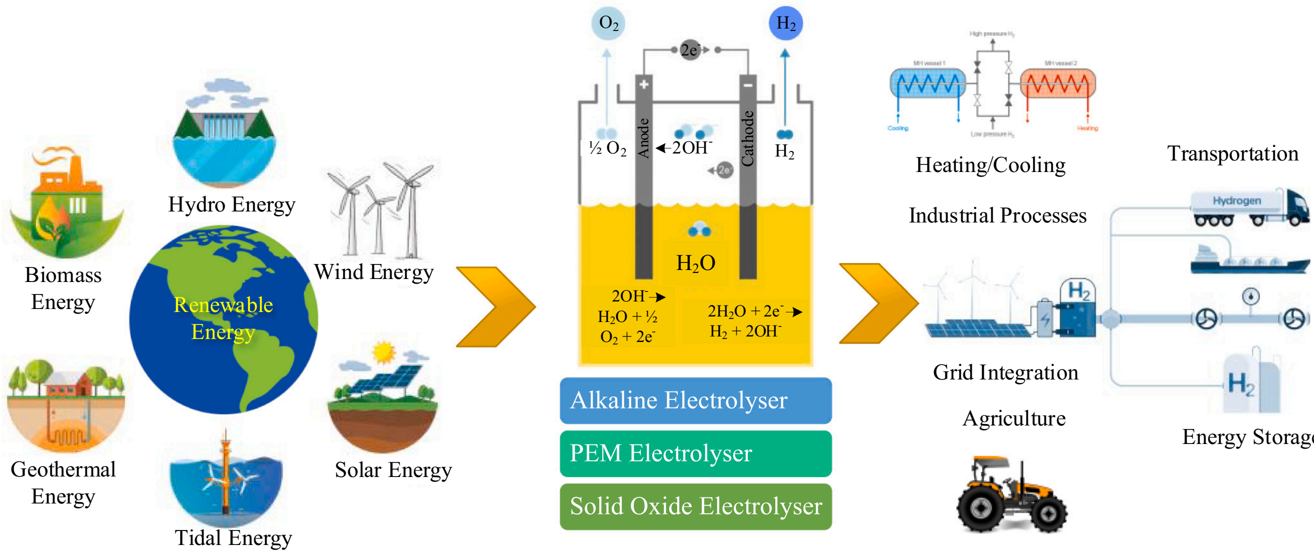

Fig. 1. Hydrogen production process through water electrolysis using different types of electrolyzers.

incorporate a variety of innovative approaches that hold promise for increased efficiency, sustainability, and cost-effectiveness. Solid Polymer Electrolyte Electrolysis (SPE) employs a solid polymer electrolyte membrane to improve system durability and performance by reducing gas crossover and enhancing chemical stability, among other advantages [108]. Photoelectrochemical (PEC) water splitting utilizes semiconductor materials as photoelectrodes to convert solar energy directly into hydrogen, with ongoing research focusing on the development of efficient and stable photoelectrodes for scalable solar-driven hydrogen generation [109]. Biological electrolysis, also known as microbial electrolysis, utilizes the metabolic activity of microorganisms to facilitate the splitting of water and facilitates the sustainable production of hydrogen from a variety of feedstocks, offering the possibility of low-energy and waste-to-hydrogen conversion [110]. High-Temperature Electrolysis (HTE) utilizes solid oxide or molten salt electrolysis cells to increase efficiency and facilitate the co-production of high-temperature heat at elevated temperatures [111]. Through improvements in electrode materials, catalysts, and system designs, advanced alkaline electrolysis technologies seek to improve the efficacy and durability of conventional alkaline electrolysis [112]. Using salinity gradients to fuel electrochemical reactions, Reverse Electrodialysis (RED) offers the potential for hydrogen production from renewable sources such as seawater and brackish water [113]. Emerging electrolyzer technologies represent ongoing efforts to optimize hydrogen production methods, furthering the objective of a sustainable and efficient hydrogen economy.

A patent is one of a tech startup's most valuable assets. Because of the market exclusivity, licensing fees, and potential partnerships that might

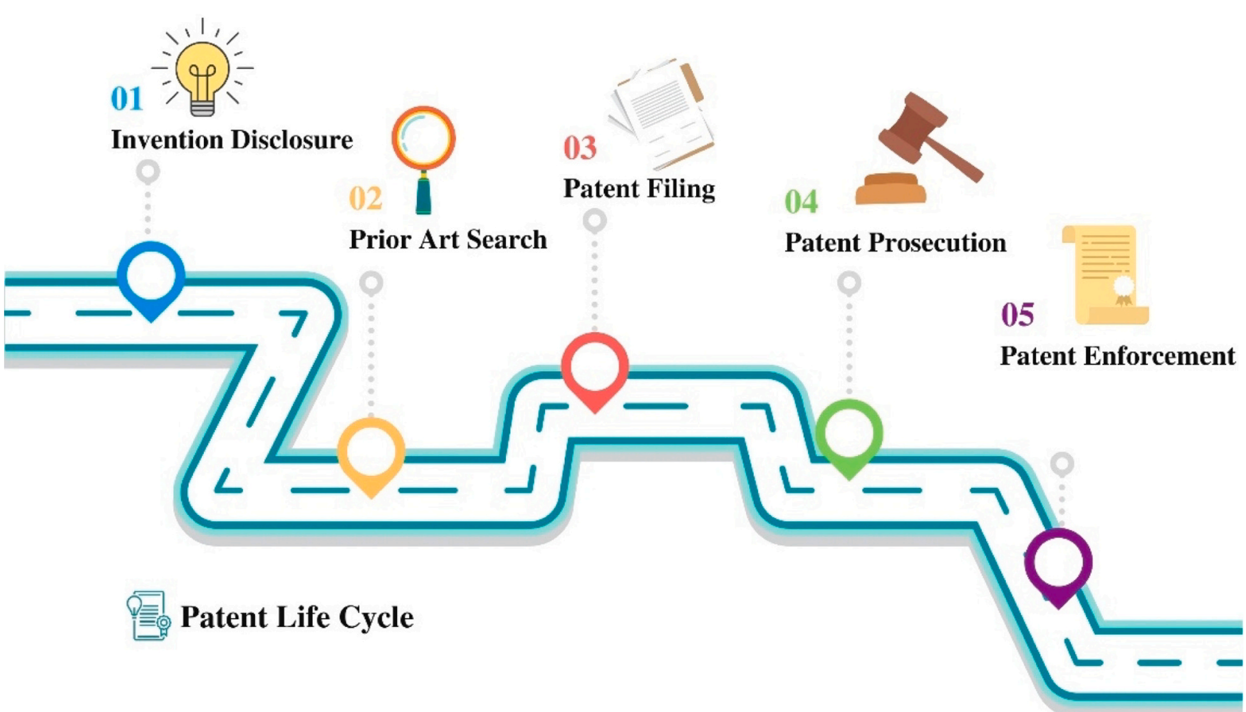

Fig. 2. The patent life cycle until patent being granted.

result from patent registration, it is now widely recognized as a crucial commercial move. It is easy to overlook the wealth of information that can be gleaned from other people's patent applications, such as the affiliations of patent owners, the legal frameworks within which they operate, and the specifics of the technologies at play (such as how they are used, the features they employ, the problems they aim to address, etc.). As a result, strategic planning and well-informed decision making may benefit greatly from patent analytics, and the in-depth examination of other people's patent filings. One of the most important types of intellectual property is patent analysis, also known as patent analytics, which is used as a policy and decision-making support tool by organizations to analyze patent documents and other data gathered throughout the patent lifecycle as shown in Fig. 2 (patent information) to spot emerging patterns in patenting and technological development [114]. The life cycle of a patent begins with the invention of an idea and concludes with the granting of a patent, and the inventor must take certain actions to transform the idea into a legal patent. The patent life cycle consists of five phases such as invention disclosure, prior art search, patent filing, patent prosecution and patent enforcement, respectively.

The strengths, resources, and gaps of an area are written out in detail in a Landscape Analysis. It's a guideline for making sure a service is rooted firmly in what locals want and need. The ability to make confident choices is strengthened by the results of a Patent Landscape analysis. Patent Landscapes' information paves the way for development opportunities and evidence-based decision making. This study's analysis and research are motivated by the need to advance electrolyzer technologies for the production of hydrogen energy. The driving force is the global transition to clean and sustainable energy sources, with hydrogen playing an essential part in decarbonization initiatives. The research seeks to identify the prevailing state of electrolyzer technologies, identify emergent trends, and address research limitations in the field by analyzing the patent landscape and providing technological updates. The need for improved productivity, practicality, scalability, and bridging the gap between research and practical applications are examples of these gaps. The ultimate objective is to contribute to the development of electrolyzer technologies, thereby facilitating the widespread implementation of hydrogen as a renewable energy solution and facilitating the transition to a more sustainable future. This research, however, conducts a patent analysis and landscape review of these electrolyser control technologies for hydrogen production. Therefore, the following are the novel contributions of this analytical study.

- This study helps to decide what to accomplish with patent analytics. This might be anything from creating a new product or innovating to monitoring the competition and keeping up with technological developments.
- Figure out which database may be utilized to search for patents to determine the boundaries of accomplishment with the desire technologies.
- Identify the responsibility for the development of technological innovation to carry out predictive analysis on how the sector will develop in the future. Describe the major participants and the different types of collaborative structures.
- Furthermore, based on the analysis of existing patents and their issues, it proposes potential directions for the future sustainable development on the efficient electrolyser control technologies towards hydrogen generation.

2. Literature review on electrolyser control technologies for H_2 production

The rise in global population and the rise in the average quality of living have both contributed to the progressive growth in today's global energy usage. In addition, as global warming and environmental pollution continued to worsen, it became more important to research and produce alternative, eco-friendly forms of energy. Hydrogen is one of the most promising clean and sustainable energy carriers; all that is produced as a byproduct of hydrogen energy production is water, and no carbon is released [115]. Hydrogen generation using water electrolysis is not cost-effective owing to its poor efficiency, which stems from its high energy requirements and slow hydrogen evolution rate. In light of this, numerous scientists have worked on developing alternative low-cost electrocatalysts, efficiency, and energy reduction [116]. The growing demand for energy throughout the world combined with the decreasing availability of fossil fuels necessitates the development of novel energy methods that leave no trace of their usage in the environment [111–113]. Green energy sources are increasingly seen as competitive with conventional energy infrastructures that rely on fossil fuels. Thus, less than 1 % of global hydrogen demand has been fulfilled by green hydrogen, defined as hydrogen produced from renewable resources [117,118].

2.1. Comparative study on different types of electrolyser for H_2 production

The primary differences between PEM, AEM, ALK, and SOFC electrolyser are their working temperatures, electrolytes, and membranes. Alkaline water electrolysis is a well-established technology with widespread commercialization. However, ALK development is hampered by the caustic liquid electrolyte, low operating pressure, and low current density [116]. The Korea Institute of Energy Research (KIER) carried out research to enhance the efficiency of alkaline water electrolysis, which is the most commercially viable and established technology for water electrolysis [117]. Unlike ALK, which has been available for quite some time, the majority of SOFC technology is still in the R&D phase. Solid oxide fuel cells have to overcome durability and stability challenges to achieve a commercial breakthrough, which Sunfire is currently commercializing [63,118]. As such, AEM makes an effort to merge the best features of PEM that are clean water input, membrane separation with ALK that are abundant and inexpensive catalyst. There is now a commercial version of Enapter's AEM system [119]. Research into AEM, however, continues to concentrate on the membrane and electrocatalyst development, with the ultimate objective of creating stable AEM as well as high-efficiency and low-cost devices [120]. The PEM outperforms the ALK, SOFC, and AEM in a number of ways, including its high voltage efficiency, good partial load, extremely high gas purity (99.999 %), ability to switch between electrolyser and fuel cell operating modes [121–123], the rapid dynamic response time when coupled with renewable energy sources or for grid stabilization [124,125], and capability to operate at significantly high pressure [126,127]. By switching to high pressure mode, an electrolyser may provide compressed hydrogen to the end-user [128–130] with little additional effort needed to hold the hydrogen in a compressed form. While the greatest pressure of commercially available PEM water electrolysis generated hydrogen is 700 bar [131], typical output pressures are in the range of 30–50 bar [33,40,43]. High-pressure operations of PEM with huge capacities raise safety concerns, which may account for the considerable discrepancy. Market trends suggest that big capacity PEM provides modest output pressure, whereas small-scale PEM is built for exceptionally high output pressure. The former is aimed at the commercial sector, while the latter is marketed at consumers interested in home use or distributed hydrogen generation such as hydrogen fueling stations. The production of high-capacity PEM suitable for exceptionally high-pressure operations with low energy consumption is the current challenge [131].

Hydrogen gas's primary issue with being used as a fuel is its shortage in nature and the necessity for cheap manufacturing techniques [132]. Many different methods exist for creating H_2, and these methods may be roughly classified into two broad groups: conventional technologies and renewable technologies. Hydrocarbon reforming and pyrolysis are

examples of the first kind of fossil fuel processing. Steam reforming, partial oxidation, and autothermal steam reforming are all chemical processes that contribute to the hydrocarbon reforming process. Producing hydrogen from renewable resources like biomass or water falls under the second category. These techniques, which use biomass as a fuel, may be broken down into two broad groups: thermochemical processes and biological processes [133]. Direct and indirect biophotolysis, dark fermentation, photo-fermentation, and sequential dark and photo-fermentation are the most important biological processes, whereas pyrolysis, gasification, combustion, and liquefaction are the most important thermochemical technologies. Methods that only use water as a material input to create hydrogen gas (H_2) include electrolysis, thermolysis, and photo-electrolysis, which comprise the second category of renewable technologies [133]. Hydrocarbon reforming and pyrolysis are two of the most common methods for extracting hydrogen from fossil fuels, although there are others. These techniques are the most refined and widely employed and providing almost all of the world's hydrogen needs. In particular, as of now, 48 % of hydrogen was created using natural gas, 30 % using heavy oils and naphtha, and 18 % using coal [134,135]. Since the cost of producing hydrogen is directly proportional to the price of fuel, which is now at reasonable levels, fossil fuels continue to play a starring role in the world's hydrogen supply. Membrane reactors are novel methods for H_2 synthesis from conventional fuels, as they are in many other areas of the chemical and biological industries. A membrane is a structure that is often considerably larger laterally than its thickness, and it permits mass movement under a gradient of driving forces (concentration, pressure, temperature, electric potential, etc.) [136].

2.2. Hydrocarbon reforming: processes and operational characteristics

Hydrocarbon reforming involves the conversion of hydrocarbon fuel into hydrogen [33]. Steam reforming utilizes steam as a reactant, while partial oxidation utilizes oxygen. Combining these processes creates autothermal reforming [33]. These methods use catalysis to convert hydrocarbon and steam into hydrogen and carbon oxides [137]. Various raw materials, such as methane, natural gas, ethane, propane, butane, pentane, and naphtha, can be utilized [138]. Pressure Oxidation (POX) breaks down steam, oxygen, and hydrocarbons to produce hydrogen and carbon oxides. Non-catalytic processes can handle methane, heavy oil, and coal at higher temperatures, while catalytic processes operate at approximately 950 degrees Celsius [139]. Autothermal reforming (ATR) combines endothermic steam reforming with exothermic partial oxidation [140]. Although hydrocarbons currently serve as the primary feedstock for hydrogen generation, integrating renewable technologies is crucial for the future as renewable sources are projected to surpass conventional ones due to the decline of fossil fuels and increasing environmental consciousness [141–144].

The solid oxide fuel cell (SOFC) has the potential for a long lifespan of 40,000–80,000 h [145], is silent in operation, emits little CO_2, and is among the most fuel- and cost-efficient power generating technologies available. The electrolyte used in a SOFC is most often yttrium-stabilized zirconia (YSZ). The oxygen molecules in the oxidant gas (air) are absorbed by the SOFC's cathode, where they are then reduced to oxygen ions (the negative ions) [146]. Oxide-ion solid oxide fuel cells (O-SOFCs) use an electrolyte made out of a perovskite or fluorite structure with oxygen deficiencies to provide oxygen channels through oxygen vacancies [147]. Most O-SOFCs use zirconia-based (e.g., YSZ) or ceria-based (e.g., gadolinia-doped ceria; GDC) or lanthanum gallate-based electrolytes [148]. However, proton-conducting SOFCs (H-SOFCs) transmit H^+ rather than O_2 and there is no produced water molecule at the anode side, which has various benefits, including good performance at lower operating temperatures and higher durability when utilizing hydrocarbon fuels [149]. Stable ferrite oxide structures provided by iron-based materials for SOCs offer a crucial foundation for enhancing a SOC's performance by replacing hydrogen or water in the fuel electrodes with carbonaceous fuel/feedstock [150]. Electrocatalysts based on noble metals are often employed in PEM water electrolysis, with Pt/Pd-based catalysts used at the cathode for the hydrogen evolution process (HER) and RuO_2/IrO_2 catalysts used at the anode (OER) [151,152]. The creation of cathode electrocatalysts has been the primary focus of research into the difficulties encountered by the hydrogen evolution process (HER) in PEM electrolysis [153]. Commonly employed catalysts for the hydrogen evolution process have been platinum (Pt) based materials in earlier research [154,155]. The two most frequent oxides used in alkaline electrolysis are nickel and cobalt, while the most common liquid electrolyte is 30–40 % KOH [156,157]. A porous diaphragm separates the anode and cathode chambers, allowing hydroxyl ions to pass through but preventing hydrogen and oxygen from doing so [158]. The diaphragms may be crafted from a variety of materials, including ceramic oxides like asbestos and potassium titanate, or polymers like polypropylene and polyphenylene sulfide [159–161]. Solid Oxide Fuel Cells are reversible due to their ability to operate in both fuel cell and electrolysis modes. The electrochemical reactions and operational characteristics of SOFCs in fuel cell mode and electrolysis mode are different. SOFCs function as electrochemical devices in fuel cell mode, using fuel and oxygen to generate electricity, water, and heat via oxidation and reduction reactions [145]. The mode obtains high energy conversion efficiencies, typically eclipsing 50 %, making it appropriate for applications involving power generation. While the electrolysis phase utilizes an electrolysis cell powered by an external source of energy to separate water into hydrogen and oxygen [146]. This mode requires the input of electrical energy and can attain hydrogen production efficiencies between 60 and 80 % [145,146]. The fuel cell mode prioritizes electricity production, whereas the electrolysis mode prioritizes hydrogen production. In fuel cell mode, SOFC typically functions at temperatures between 600 °C and 1000 °C to obtain high ion conductivity and efficient power generation [146–149]. In contrast, in the electrolysis mode, the operating temperature can be altered to optimize hydrogen production efficiency while preserving water-splitting kinetics [150].

2.3. Hydrogen as a future fuel: Storage, utilization, and sustainability

Hydrogen has a high energy density per mass and is thus a possible future fuel. When compared to the 12-kWh found in a kilogram of gasoline or diesel, hydrogen's energy density is far higher at 33.33 kWh [162]. Hydrogen is often stored at pressures of up to 700 bar in steel gas cylinders. About 75 % of the world's subterranean hydrogen storage is in depleted deposits [163]. Under optimal conditions, the maximum pressure within a salt cavern may reach 200 bars, and its volume can be anywhere from 1,000,000 to 1,000,000 m^3 [164]. Liquid hydrogen is another mean of compactly storing hydrogen; it may be transformed into a liquid at low temperatures ($20-21K$) and ambient pressure, and its realized volumetric density can approach 70.8 kg/m^3; this is slightly greater than the density of solid hydrogen, which is 70.6 kg/m^3 [164]. Due to their large hydrogen storage capacity, metal hydrides have recently gained a lot of attention [165]. At standard conditions (room temperature and atmospheric pressure), palladium can absorb hydrogen at a rate of 900 times its own volume [166]. Both [167,168] provide in-depth analyses of the practical applications of metal hydrides and the mathematical studies of sorption/desorption process modelling in metal-hydride systems, respectively. Models of the high-pressure metal hydride bed and vehicle heat exchange using dynamic system simulation have been studied in [169,170]. Efforts have been undertaken to reduce the price, optimize the operating temperature, and improve the thermal management of the system in preparation for the industrial development of metal hydrides [171].

Since hydrogen is useful for a wide range of energy storage and transmission purposes. Several methods of storing energy already exist, such as pumped hydro, compressed air, batteries, and so on [172]. Hydrogen, on the other hand, provides a higher energy storage capacity,

a longer storage time, and more adaptability than these other options. It may absorb surplus renewable energy output in particular, hence reducing energy price fluctuations and uncertainty [173]. While battery-powered cars are limited by their ability to travel great distances, hydrogen-fueled electric powertrains eliminate this problem. It is predicted that hydrogen-fueled vehicles would account for 3 % of worldwide sales in 2030 and as much as 36 % by 2050 [174]. The use of Energy Storage Systems (ESS) with conventional electricity to create a hybrid microgrid is crucial for mitigating the unpredictability and increased intermittent of RESs. By incorporating hydrogen technology into ESS, researchers may achieve various technical and economic goals, including better management of the system's energy flow [175]. There are several factors involved in hydrogen production, such as temperature, irradiation, membrane quality, diffusion limit current, and short circuit current [176]. High volumetric hydrogen densities, low operating temperature and pressure, ultra-pure hydrogen release, and significant advancements in safety make alloys an attractive option for stationary hydrogen storage [177]. Although compressed hydrogen storage has several useful applications in the fuel industry, the approach is severely constrained by the need for a high-pressure tank [178]. Hydrogen is now stored using either a compressed gas or liquid state storage technique, however the future of hydrogen storage lies with the solid-state storage approach. In addition to magnesium-based alloys and intermetallic compounds, complicated hydrides and chemical hydrides are also part of the solid-state storage approach [179]. Improved efficiency and safety in hydrogen storage and dispensing systems, as well as novel, environmentally friendly ways of creating hydrogen, are the primary areas of current hydrogen fueling station research [180]. Public institutions may promote innovation, facilitate the transfer of knowledge, and address environmental concerns related to hydrogen production by funding research and collaboration. This, in turn, will encourage the widespread acceptance of hydrogen as a renewable energy source and have beneficial effects on the environment by reducing carbon emissions while encouraging sustainable energy solutions [181]. Eco-innovations, which emphasize sustainability and concerns about the environment, help improve electrolyser technology for a better future. These inventions improve energy efficiency while lowering carbon emissions and having minimal impact on the environment. It involves the development of cutting-edge materials, effective production techniques, and the incorporation of renewable energy sources. Electrolyzer technology plays an essential part in the clean energy transition by emphasizing eco-innovations and enabling the widespread use of environmentally benign hydrogen as a renewable energy source [182].

3. Methods for patent search

The searches were conducted using the Lens database, looking for patent published to better understand the researchers and inventors with valuable technological information needed to find innovative solutions to technical problems in the field of “Electrolyser control technology” for the production of hydrogen. The primary goal of this analysis is to provide a clear picture of technical advancement and innovation in electrolyser control technology for hydrogen production and comprehend the nature of the patent available in this field. The Lens database was assessed for patent data concerning developments in electrolyser control technology for hydrogen production between 2002 and 2022. This free and public database comprises over 249 million documents encompassing over 142,5 million patent families from around 105 countries. The Lens database has 36,7 million authors and 16,6 million applicants for patients. The search design allows documents to be retrieved via patent classification codes and also facilitates long search strings. Furthermore, it provides advanced filtering features, such as date type as well as the document type. Hence, it is possible to separate the data for the filing dates of patent applications from the publication date of granted patent papers. Moreover, the database allows the grouping of patent records within simple patent families, that reflect the entire collection of documents relevant to a certain innovation, encompassing filings including patents over several jurisdictions.

Using the Lens database and analytics platform's FrontPage, English Title, and/or Abstract search keywords for any topic were conducted, followed by “hydrogen production” keywords. Using Microsoft Office Excel, the data was then retrieved and analyzed. The retrieved data were then collated into a Microsoft Excel-formatted spreadsheet and dashboard including information such as Application Id, Application Number, Publication Date, Country, Title, Abstract, Applicants, and Inventors. After that, every aspect of the listed patents was extensively inspected and classified into the appropriate category. The query results were filtered by the Document Type of Granted Patent and the Publication Date ranges for each year from 2002 to 2022. The numbers of issued patent papers and related patent families were recorded each publication year in addition to the cumulative totals over the 20-year duration. From the data set that was filtered over a 20-year range of Publication Date, the top jurisdictions and applicants were found, along with their respective numbers of issued patent papers. For applicants, the totals of awarded patents were made more representative by adding together name variants and subsidiaries. No patent with the same patent number was recorded more than once, although patents filed as various patent types were counted numerous times.

3.1. Research design structure

The search for patents was undertaken in November 2022, and a total of 490 patent papers were acquired. The final selection of 107 papers from the Lens database was determined using the following method:

- A total of 490 patent papers were selected initially from the Lens Database using the specific keywords including “Electrolyser”, “Control” and “Hydrogen”.
- At first screening total of 222 papers were filtered by family option using “Group by excluded family” and this help to exclude the similar patent papers.
- At second screening total of 165 patent were filtered by set limit to English Language.
- The third screening is conducted by excluding papers related to materials, and electrochemical. Based on these conditions of the third screening, a total count of 131 articles were selected in the third screening.
- Finally, a sum of 107 patent papers from the well-defined Lens database published by several applicants were chosen for the final analysis.

Fig. 3 shows the overall selection process for the patent papers extracted from the Lens database for the electrolyser control technology for hydrogen production.

3.2. Limitations of patent search

The patent landscape analysis is a technique that is frequently used for reviewing recent advances, analyzing a specific field of research, and evaluating the impacts and interactions between a wide variety of various fields of study. Nevertheless, there are a few limitations that need to be mentioned about the findings.

- Firstly, patents that are not yet accessible via the Lens website. The merging of other databases of patents that are freely accessible to the public, such as the Scopus database and the Derwent global patent database, might be an idea to consider about for potential future proposals.
- Secondly, the patent titles and abstracts which did not include any references to the electrolyser control technology for hydrogen

Fig. 3. The selection process for patent papers of electrolyser technologies for H2 production using Lens database.

production were dropped from the contention for the top spot in the final selection.

- Thirdly, for the purpose of the study, only patents that were issued in the most recent 20 years (between the years 2002 and 2022) are considered.
- Fourthly, basic patent families are the only ones that are taken into consideration for the study while using the database. In the end, a particular topic area is taken into consideration, and the patents that take into account keywords like "electrolyser," "controller," and "hydrogen production" are the ones that are selected from the final patent database.

Despite the limitations that were discussed above, patent landscape analysis is an essential technique that is used all over the globe to get an understanding of the research, market trend, and commercialization strategy in a certain areas of research exploration.

4. Patent landscape analysis on electrolyser technologies

A total of 107 patents on electrolyser control technique for the production of hydrogen were found. Analyzing patents may be valuable for monitoring technological advancements and gaining insight into technological advancements. Patent data, for instance, may identify economically significant R&D hotspots and validate the global status of individual nations. As in most of the new technologies, the earliest patent filings represent technological advancements and commercial information. Patents are also one of the predictability indicators for technological and commercialization developments. This study analyzes the technological advancement of electrolyser control technologies for improving researchers with information on hydrogen production patent technology development. The analysis is based on patents over time, patent applications by date of publication, filing, and grant, document types, legal status, jurisdiction, and the most cited patents for developing electrolyser control technologies, which have previously been among the most productive and competitive in terms of patenting activity. In addition, we analyze some of the most active patenting sectors for hydrogen-based technology.

4.1. Growth of patents overtime

The volume of patent applications filed throughout duration that have a long-term effect on a particular sector for potential future study and research advancement is referred to as the growth of patents. The patent analysis shown in Fig. 4 illustrates patent records over time. From 2002 until 2022, data on granted patents, limited patents, and patent applications has been compiled in the graph. Based on a patent landscape analysis conducted between 2002 and 2022, the current research focuses on advancements in the area of electrolyser control systems for hydrogen production. Fig. 4 depicts the breakdown of the total growth into two phases: phase 1 (2007 to 2010), and phase 2 (2018 to 2022). The graph shows that there seems to be a steady improvement in the filed patent applications since 2007. There has been a significant increase in the growth of patents since the second phase of 2018 where 20 patent applications have been issued in 2022. The reason behind this surge is due to the worldwide campaign for renewable energy and decarbonization, advancements in materials and system designs, and increased research and development efforts aimed at advancing electrolyzer technology for the production of clean hydrogen [135,157,179].

There are 79 patent applications, 25 granted patents, and just three categories of limited patents are published out of a total of 107 patents as shown in Fig. 5. Only 25 of the 107 patents granted are legally protected. If you have been granted a patent, no other person or business can legally profit from the work, including manufacturing, using,

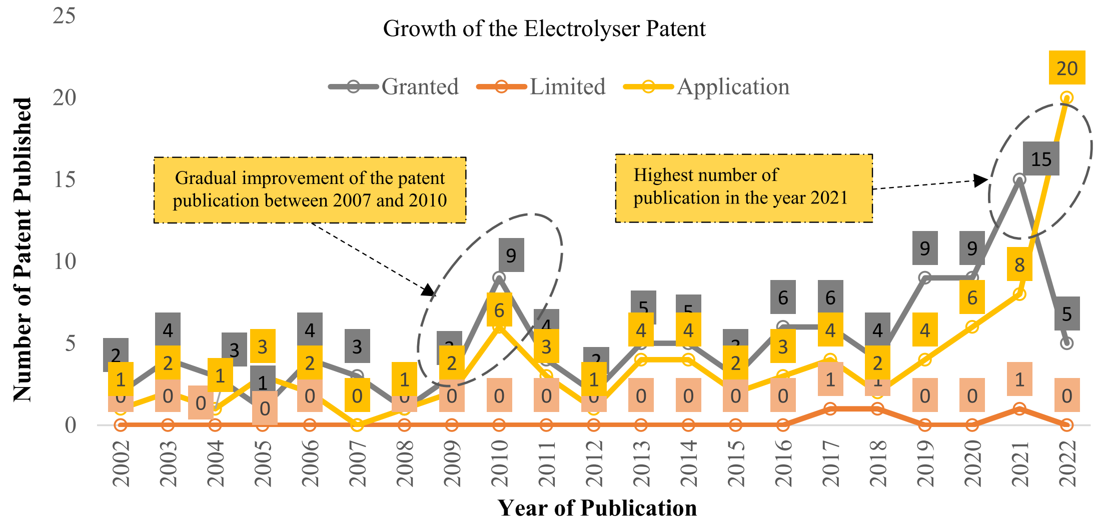

Fig. 4. The total growth records of patents overtime.

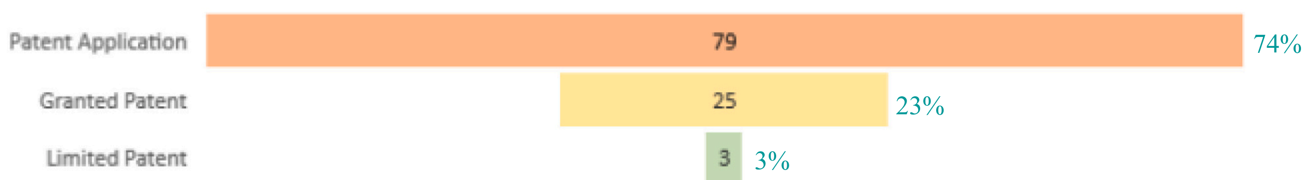

Fig. 5. The documents by type of the patent papers in terms of applications, granted and limited.

selling, proposing to sell, or importing it. There are only three limited patents, each of which is a specific sort of patent with certain policy-making features, such as approval for several years and varying validity between countries.

4.2. Patent application by date of publication, filing and grant

Although there is a long-standing correlation between the number of patent applications and infrastructure prosperity, the number of granted patents is a reliable indicator of innovative quality and economic significance. Only patents that comply with the patent granting requirements will be granted. The trend of filed, granted, and published patent applications is shown in the bar graph in Fig. 6. The published, granted, or filed year of the patent is shown along the horizontal axis from 1998 to 2023. The highest number of patents published in 2022 is 22, while the highest number of patent applications filed is 15 and the highest number of granted patents is 6 in 2021. The progression over time demonstrates the patent owner's commitment to devote resources to safeguard the market share where the innovation may be utilized to earn revenue. The number of granted patents has increased steadily over time, indicating a general growth in the capabilities obtained for the creation of new electrolyser control technology for the production of hydrogen.

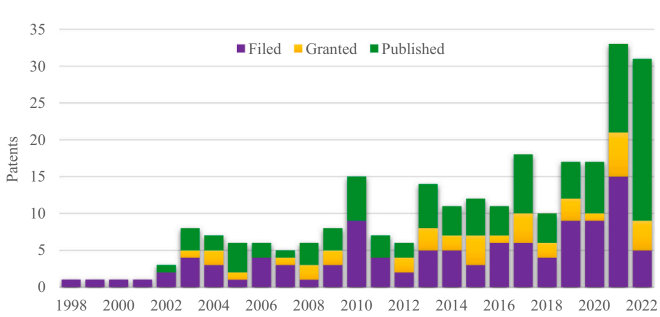

Fig. 6. The patent documents by published, date of granted and filed.

4.3. Patent documents by legal status

Patent Legal Status is a crucial piece of the patent information jigsaw because it enables industry experts to answer a question that is key to their everyday activities. During the route from the creation of the fundamental concept to the patent's expiry into the public domain, a patent may be engaged in a variety of events that have the ability to change its legal position, as well as its financial value, as we will see

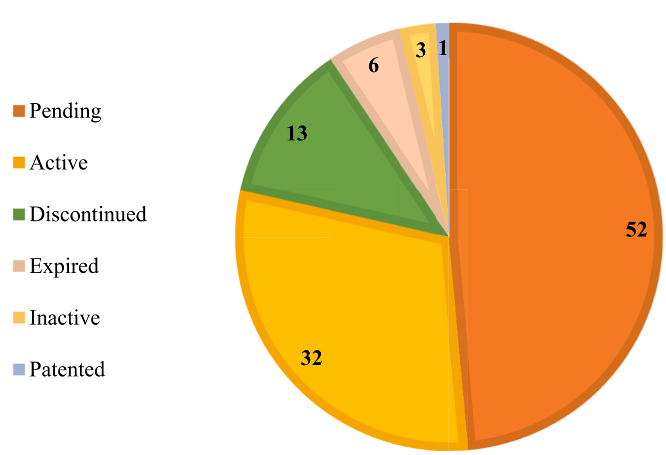

Fig. 7. The patent documents by legal status.

below. Fig. 7 shows the patent documents for 107 publications by their legal status. 52 of the total patent papers are pending, which indicates that the patent office has received the patent application but has not yet rendered a final decision. 32 of the papers are active, which indicates that the patent has been awarded and its owner may now enforce or monetize the invention in accordance with its business plan. Since three of the articles have been inactive, the patent can no longer be enforced or monetized. The applicant abandoned the application, the assignee withdrew the patent, the assignee has not paid the maintenance costs, the patent period has expired, the patent was cancelled as a result of invalidation procedures, or the patent was otherwise reissued.

4.4. Patent documents by jurisdiction

The global patenting activity or jurisdiction in the field of electrolyser control technology for hydrogen production is shown in Fig. 8. The World Intellectual Property Organization (WIPO), the United States, and Europe have dominated the patenting of electrolyser control technology since 2002. The patent data also reveals that the WIPO and the United States were the first to file electrolyser control technology patents. In contrast, China and Russia have increased their patent filing activity during the last two decades. Romania and Spain are another two important nations making major progress in patenting activities in this area. WIPO has 40 patents, but the United States and Europe are in close pursuit with 38 and 22 patents, respectively, in the area of electrolyser control technology for hydrogen generation.

Applicants are the organization or individual that files the patent application. It can be the original inventor, or it can be the assignee. Fig. 9 shows the top applicant for the patent of the electrolyser control system for hydrogen generation in which some of the patents filed under this selected 107 number are by original inventors, while others are by individual applicants. To visually distinguish each jurisdiction, the figure provides colors that represent various areas. The number of patent applications filed by the applicants is shown by the thickness of the strands, with thicker strands indicating greater applications. The directional nature of the strips helps to identify the jurisdiction or territory from where the patent applications have been filed by the applicants. Among all of the jurisdictions, WIPO exhibits the largest number of patents, the majority of which were submitted by Hydrogenics Corp [17]. With significant patents from Air Prod & Chem [18] and Air Liquide [31], the United States has been ranked second. Since a patent application may also be made by an individual, Gopal Ravi B [98], Freeman Norman [100], and Foji Simens Khajdro Pauerhr Dzh [92] are the three top individual applicants among the top applicants for jurisdiction category.

4.5. Top 10 cited patents

The patent citation technique is very much like the one used in academia. In recent years, econometrics, scient metrics, and innovation studies have all turned their attention to the topic of patent citations. The Lens database patent information has been retrieved and illustrated in Table 1. The bl The patents with the most citations were published in 2017 and received 103 citations. The applicant is CASPO LLC, and the application number is US 2017/0016113 W [10]. The legal status is pending under the authority of WIPO. The patent by applicant MARTINREA INTERNATIONAL INC that was published in 2009 and has a citation count of 12 has the fewest citations among the top 10 cited patents [6]. There are two current patents in the top 10 that have a citation count of 36 and 43, respectively, and the applicants for those patents are GEN ELECTRIC [5] and NEXT HYDROGEN CORP [7]. These patents were published in 2008 and 2010 respectively. The factors that determine patent citations have a significant impact on electrolyser patent technology. The number and quality of citations a patent receives indicates its influence and contribution to the field. The number of citations is influenced by novelty, technical advancements, and inventiveness, while influential citations emphasize the patent's significance. Understanding these factors assists researchers in identifying trends, directing their own research, and aiding policymakers in promoting effective electrolyser technologies [183].

4.6. Key players in the market

A patent is the result of collaborative work between an organization or individual and a team consisting of an inventor, an applicant, and an owner. Those with the highest number of published patents are singled out as key players in the market of electrolyser control system for hydrogen production for this landscape analysis. From those 107

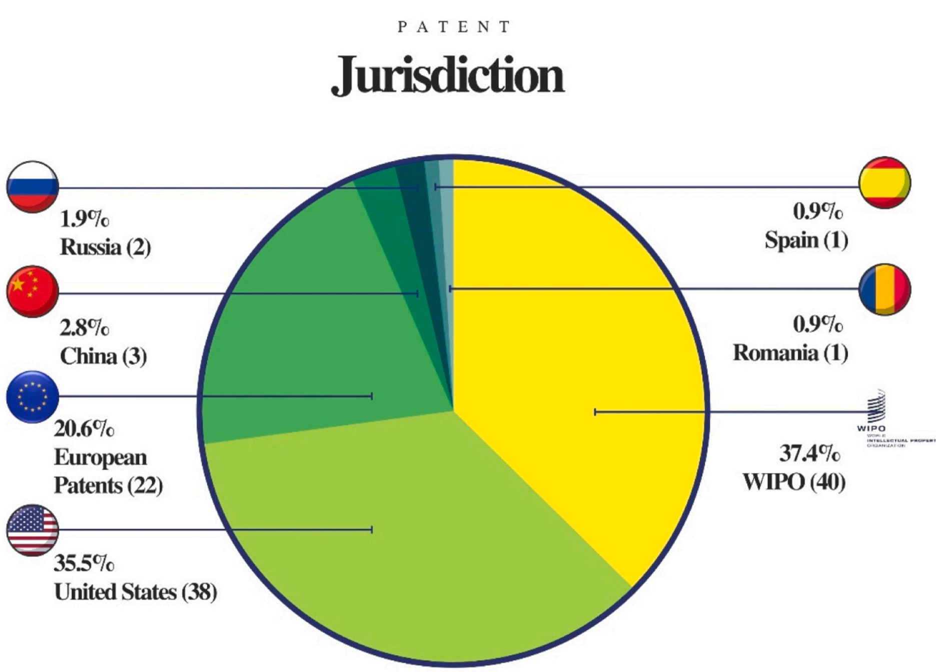

Fig. 8. The patent documents by the jurisdictions in terms of country and organization.

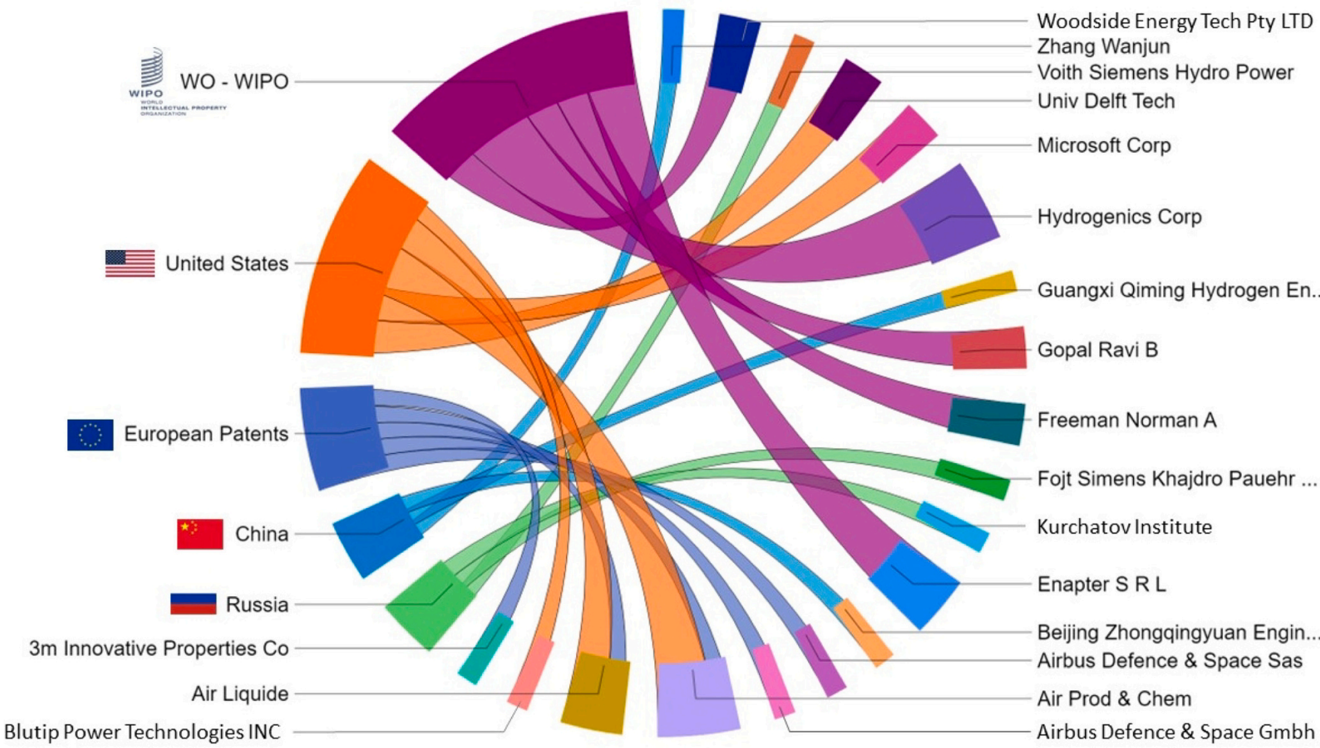

Fig. 9. The top applicants for electrolyser technologies by the jurisdiction in terms of country and companies.

Table 1
The top 10 cited hydrogen electrolyser patents from 107 patents under different jurisdiction.

	Wipo		United States				
Application Number	**Applicants**	**Jurisdiction**	**Legal Status**	**Publication Year**	**Citation**	**Ref**	
US 2017/0016113 W	CASPO LLC	WO	PENDING	2017	103	[10]	
US 43105203 A	DUNN JAMES P.	US	DISCONTINUED	2003	82	[2]	
US 38782899 A	STUART ENERGY SYS CORP	US	EXPIRED	2004	78	[4]	
US 60651709 A	NEXT HYDRO GEN CORP	US	ACTIVE	2010	43	[7]	
US 26342005 A	GEN ELECTRIC	US	ACTIVE	2008	36	[5]	
US 16220802 A	AGBOSSOU et al.	US	EXPIRED	2003	33	[3]	
US 0120032 W	NUVANT SYSTEMS LLC;SMOTKIN EUGENE S	WO	PATENTED	2002	15	[1]	
US 91115006 A	BOGERS TIMOTHY DONALD;WILLIAMS JOSEPH C	US	DISCONTINUED	2010	15	[8]	
US 83030110 A	HANSON WILFRID JOHN;HATTON IAN RAYMOND	US	DISCONTINUED	2011	13	[9]	
US 28183107 A	MARTINREA INTERNAT INC	US	DISCONTINUED	2009	12	[6]	

* LLC = limited liability company; CORP = corporation; NEXT HYDRO = NEXT Hydrogen; US=United States; WO=Wipo.

patents, we extracted the top 10 owners to represent as a representation of the dominant players in the market for patent ownership. Fig. 10 illustrates the top owners of the chosen patents. Hydrogenics Corporation has the top number of patents with the digit 5. Air Products and Chemicals INC, Stuart Energy Systems Corporation, Airbus Group INC and Acciona Energia with 3 patents each holding second rank among top owners. With 2 patents in the list Blackberry, Microsoft, Technische Universiteit Delft, and Aquahydrex are in the top owners list.

Fig. 11 illustrates the top 10 applicants in the publication of electrolyser control system patent for hydrogen production. There is multiple y-axis representing number of patents and on the secondary y-axis represents the percentage market covered by combined applicant from

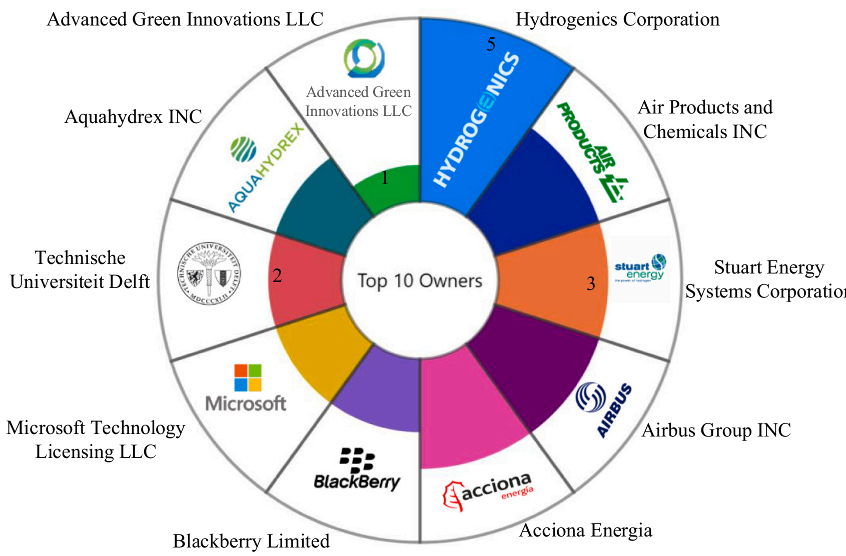

Fig. 10. The top 10 owners of the selected patents in the market.

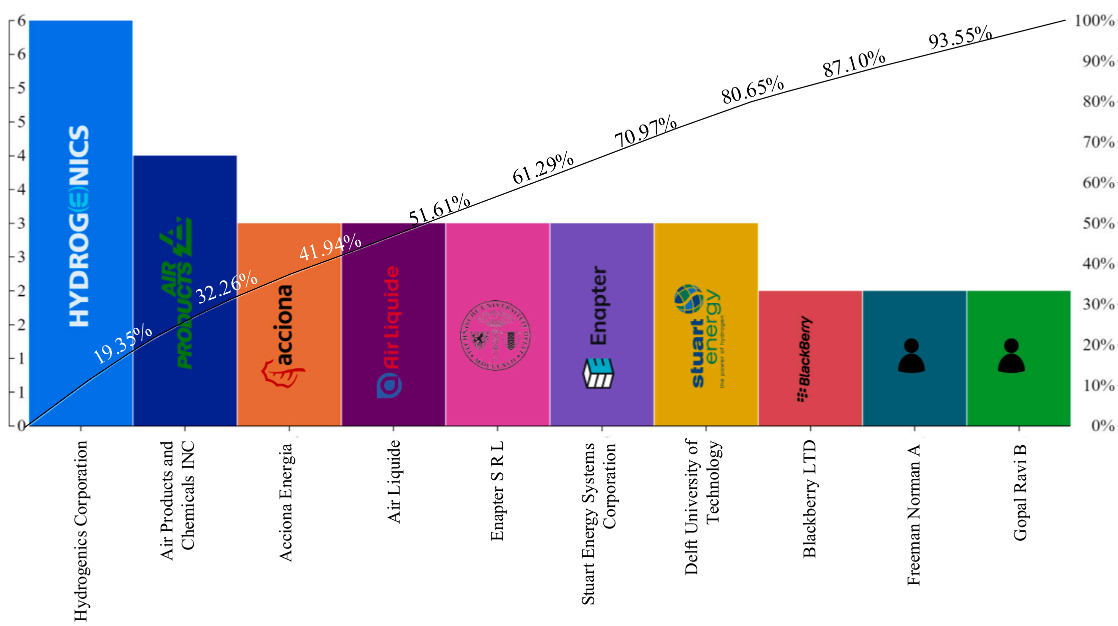

Fig. 11. The top 10 applicants of the selected patents on hydrogen electrolyser control system.

the largest to the smallest and x-axis represent the name of the applicants. Likewise, as the top owner, Hydrogenics Corp is also recorded as the highest for the patent paper with 19.35 % of the total in the top 10 applicant list. Followed by Air Products and Chemicals INC in the second with 4 patents where Hydrogenics and Air Products combine cover 32.26 % of the top market. Combined with the last applicants Acciona covers 41.94 %, Air Liquide with 51.61 %, Technische Universiteit Delft 61.29 %, Enapter 70.97 % and, Stuart Energy 80.65 % in total coverage of the top applicant market for the patent of electrolyser control system for hydrogen production. These all applicants have filed three patents each.

The top 10 inventors of the patent and their respective country of research origin are shown in Fig. 12 for the electrolyser control system development. Three of the inventors has published three patent each including Gopal Ravi B [100], Guelbenzu Michelena Eugenio [91], and Mulder Fokko Marten [35]. In addition, the rest all have done same number of patents two each for contribution of work in electrolyser control system for hydrogen production. From the Fig. 12 it can be observed that majority of the inventors are originated from Canada with a total number of 11 patents covering almost 48 % of the leading innovators list. Other countries, including Spain, Netherlands, United States, Italy, and United Kingdom have each one innovator who all have impact to the patent work.

In the patenting process, an inventor can seek the counsel of a patent agent, also known as a patent practitioner. In addition to assisting with the preparation and submission of patent applications, patent agents provide their expert views on whether or not a certain invention is patentable. Helping their clients file patent applications, conduct prior art searches, draught legally binding claims of ownership, respond to rejections, and make decisions about whether to terminate applications are all services provided by patent agents. Overall patent agents play a key role in patent publication. Fig. 13 has been developed by listing the top 10 legal agents for the 107 patents for the electrolyser control system intended for hydrogen generation where the number represents the

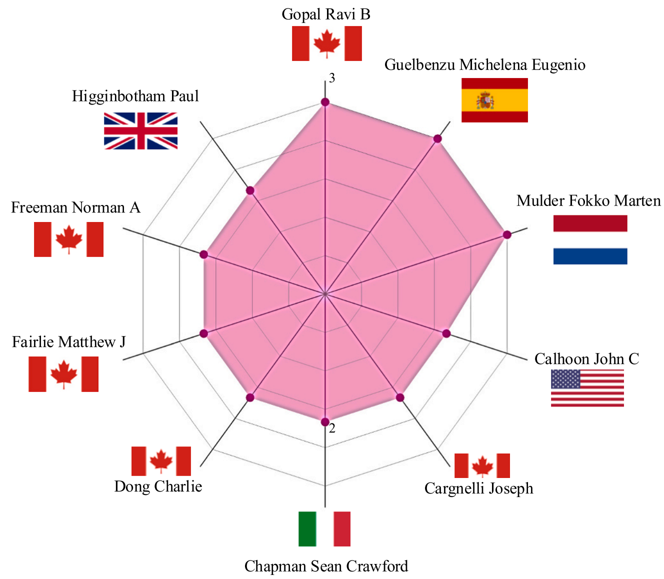

Fig. 12. The top 10 inventors of the selected patents and their country.

number of patents filed by the individual agency. Figure indicates that Bereskin & Parr and Mathys & Squire are the top two agencies in terms of the number of patents they advise on for three of the patents each. Followed by Griffith Hack, and Patentgruppen A/s in the second rank for assisting in the publication of 2 patent each and rest of the legal agent published 1 patent each.

4.7. Patent technological area for electrolyser control

The patent for the electrolyzer control method has claimed numerous technological area which has been illustrated in Fig. 14. The majority of the area claimed patent that is covered under "Material Science" with 12 of the patents in the list. Followed by Chemistry and Engineering with 10 and 9, respectively. Electrolysis of water also has nine of the patents claimed work in this field. Environmental science, process engineering, and Renewable energy sector have been claimed by 8 of the selected patents. Under renewable energy come wind power and solar energy, where their updates on the technology have been claimed in 7 and 4 patents, respectively.

4.8. Co-classification analysis based on CPC

The idea of this co-classification aims to enhance the CPC analysis by determining and designating categories to a set of data. The analysis was performed utilizing information from the Lens database, that contains the selected 107 patents. The purpose of a classification analysis is to figure out what characteristics are used to make that determination. The fundamental goal of filing for a patent is to safeguard innovations against imitation by competitors. IPC and CPC codes are used to classify patents into various technical fields, making it simpler to locate relevant patent papers and giving each invention its own identity. Back in 2012, USTPC and EPO developed CPC with 250,000 codes to enhance searchability. Each CPC code indicates a distinct technological topic area, thus by using features extraction technology to combine them, new information resources may be generated. Fig. 15 lays forth the format of the CPC patent categorization code.

Patent filings related to electrolyser control system for hydrogen production are verified using codes like Y02E, C25B, Y02B, Y02P, and H01M. The data for the 107 patents has been divided into numerous groups according to their respective topic areas. A total of 107 patents are selected and distributed into many subgroups according to their subject categories. Fig. 16 demonstrates the classification of patent filings related to electrolyser control system from highest to the lower

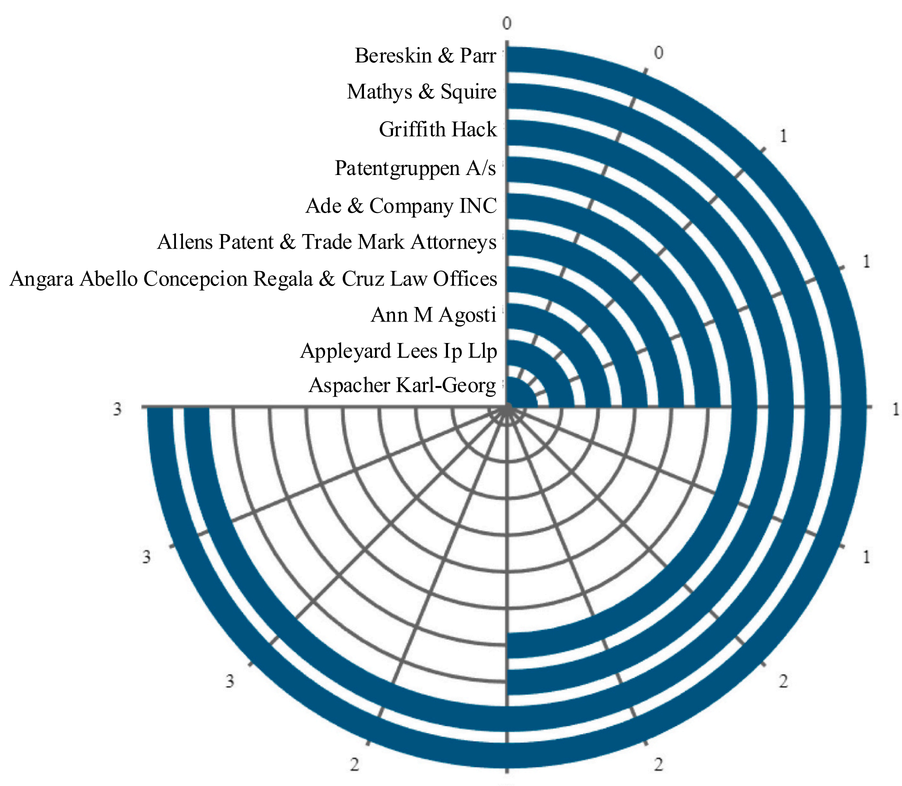

Fig. 13. The top 10 legal agents of the selected patents.

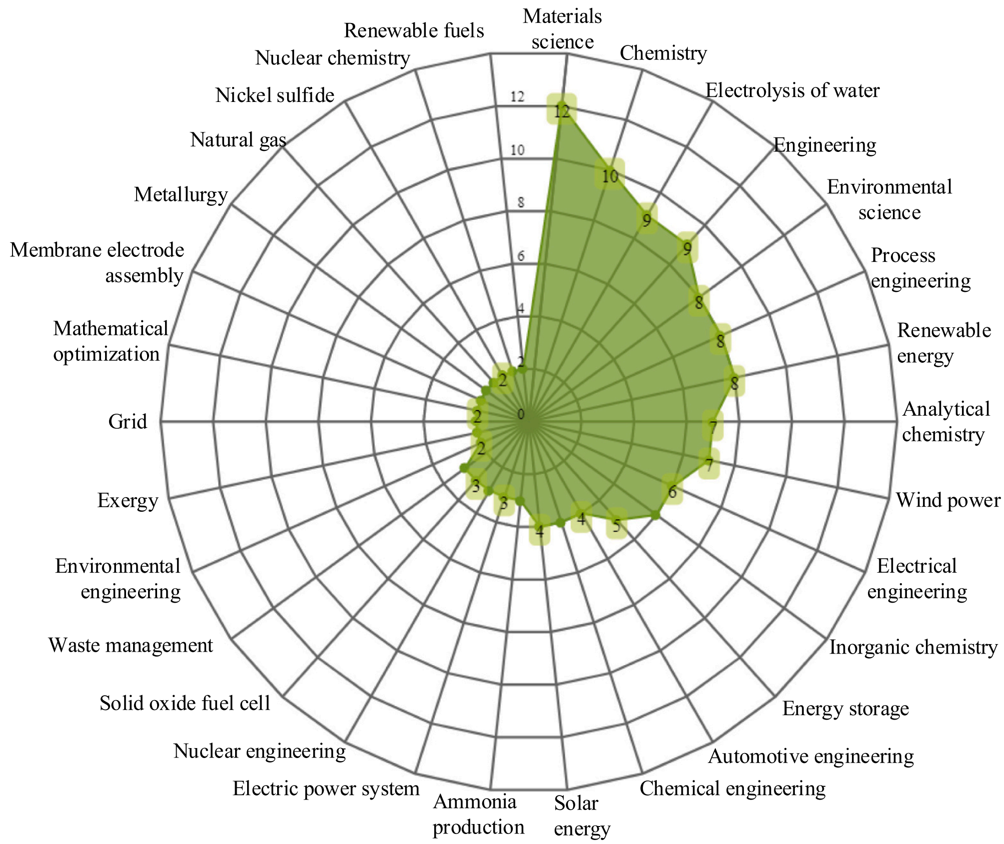

Fig. 14. The technical area for electrolyser control technologies of the selected patents.

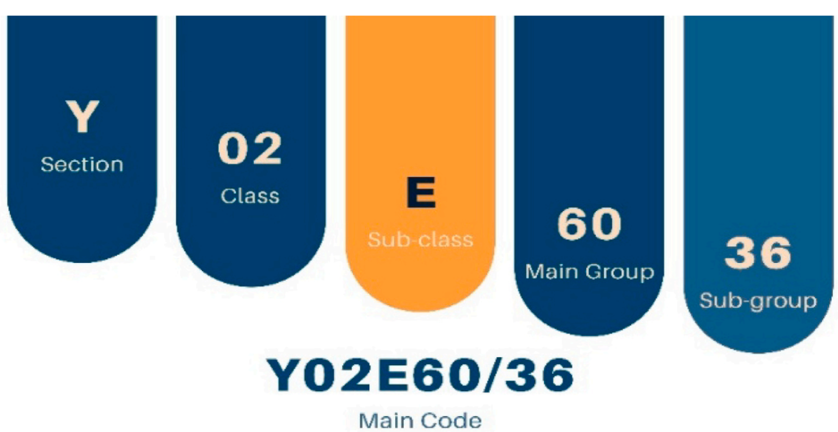

Fig. 15. The structure of the cooperative patent classification.

number of patents for hydrogen production in terms of key CPC subgroups.

Patents have been selected from the year 2002 to 2022 and the distribution for the CPC codes has been illustrated in Fig. 17. A steady growth of patents connected to the electrolyser control technology for hydrogen production is rising from 2017 as per the Fig. 17. Furthermore, a precipitous rise in Electrolysis of water and Hydrogen production from non-carbon sources associated inventions have increased in 2021. Likewise, the invention linked to process control in electrolyser control technology has been increased in the year 2021. From Fig. 17 it can be stated that "C25B1/04" has been used the most in the patents through 2002 and 2022 followed by Y02E60/36. Fig. 17 (a) shows the weight of the nodes for Y20E60/50 and Y02E60/36 observed to be the highest diameter as the occurrence for this code is the highest in the specific years. Followed by C25B1/04 and H01M8/0656 has been in the top list as per occurrence per year of the patents. Fig. 17 (b) shows the clearer image of the CPC codes used per year and the size of the block represents the weight of the codes and years.

5. Electrolyser control technology updates

The rapid development of today's technologies has accelerated the rate of change by facilitating more rapid evolution and advancement. The preceding five years have seen significant shifts in many areas, not the least of which are technological trends and rising technologies. Technology is always evolving, so in the next five years, we may

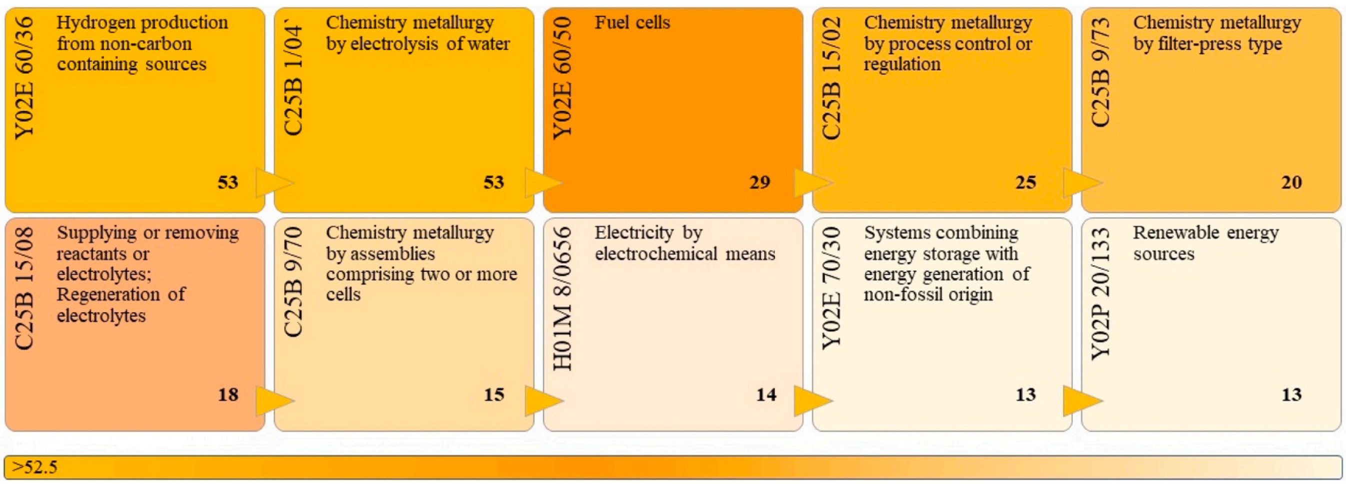

Fig. 16. The distribution of the patents in terms of key CPC sub-groups.

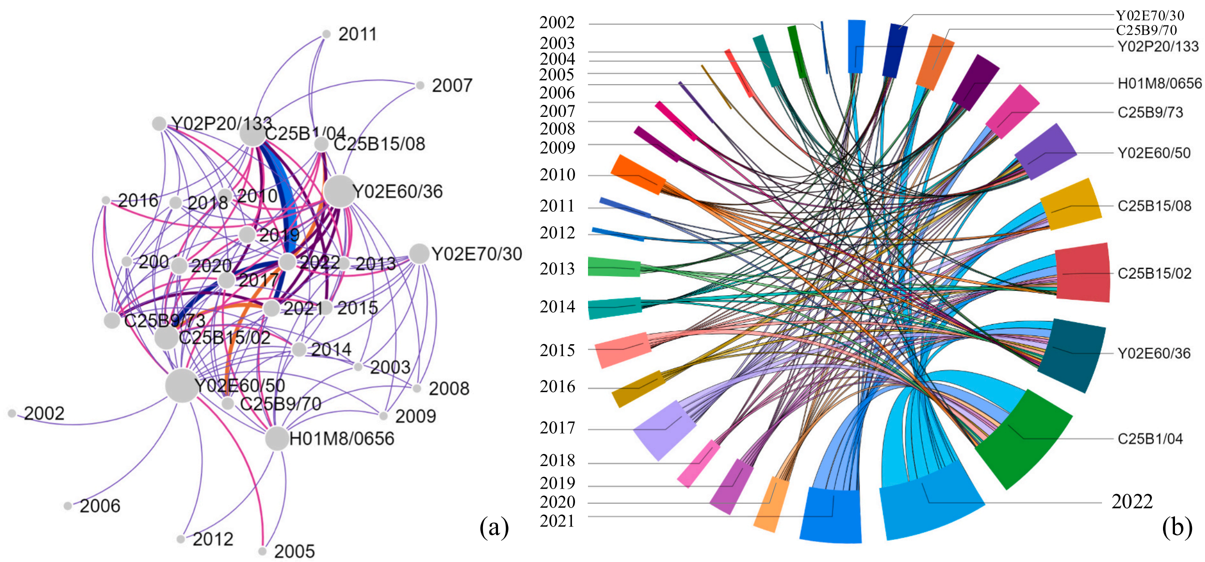

Fig. 17. The patent distribution of CPC codes (a) concentration of main codes and year (b) number of times CPC codes used per year.

anticipate a diverse range of new initiatives that will impact how we live. Here are some of the most intriguing, patented advancements over the last five years that were identified after researching through all patent technology publications. We have been reading a lot about the control system development for the electrolyser and what the future of the electrolyser initiative would entail. The world energy industry is now in need of hydrogen generation. Many individuals think hydrogen will revolutionize civilization as it develops and improves, just like the battery did. It is anticipated that this will permanently alter how we produce, utilize, and store energy, and that any development that does not integrate the energy system would perish.

5.1. *Innovation in electrolyser control: 5 years of progress*

Innovation of the electrolyser system relies heavily on a reliable method of control. Effective performance is highly dependent on the application of tried-and-true technology for designing optimized control systems. The electrolyser control technology updates in different applications over the last 5 years are shown in Table 2 that provide the information on the system's control technique and their implementation. Inventors of the specific patents developed the control method to improve its efficiency and sort out the issues and challenges in the system and designed the better electrolyser from the existing. Viltorovitch et al. implemented mesh network in wireless transceiver of anion exchange membrane (AEM) electrolyser for wireless communication wherein at least one of the one or more auxiliary devices is controlled in dependence on communicated information relating to the operation of at least one of the one or more primary devices [1]. Michael and Abraham used control discharge valve to operate at supercritical conditions for retaining fluid reaction [2]. Compressor plays crucial part between hydrogen storage tank and Electrolyser. Many inventors have patented the advancement in the compressor system. In a multistage compression system, Gerard et al. utilized the centrifugal compression stage [3]. The hydrogen gas is supplied to the centrifugal compression stage at a predetermined feed temperature, pressure, and relative humidity [3]. Other inventors also included design in the patents for compressor device. A pressure sensor has been installed in the electric motor of the condensed water separator's compressor in order to regulate the flow of liquid being compressed [4]. Ward Khamun also mentioned the compressor for regulating gas compression power [16], where Ian and Joseph also did power consumption control for their compressor [17]. Paul and Vince mentioned compressor design upgrades using the method of downstream process for producing hydrogen gas by electrolysis of water [18]. For large-Scale Hydrogen Refueling

Table 2
The electrolyser control technology has been updated in different applications over the last 5 years.

Method of Control	System	Device	Application	Ref.
Mesh Network control	Wireless communication	Wireless transceiver	Microgrid	[1]
Control Discharge Valves	Fluid Reaction	Electrolyser	Electrolyser	[2]
Centrifugal Compressor Stage	Centrifugal Compression System	Centrifugal Compressor	Compressing Hydrogen Gas	[3]
Pressure sensor	Compression system	Electric Motor	Electricity Generation Plant	[4]
Model predictive control	Renewable Power Sources	Hardware Processor	Industrial Gas Plant Complex	[5]
Time-dependent predicted optimization	Renewable Power Sources	Hardware Processor	Industrial Gas Plant Complex	[6]
Cooperative Control	Energy storage system	Hydrogen Storage Tank	Gravity storage technology	[7]
Automated oxygen flow control	Electrolysis System	Microcontroller	Hydrogen Production Plant	[8]
Electrical Load Management Control	Energy management system	Electric motor	Aircraft	[9]
Receive signals from said in-situ diagnostic means	Energy storage system	Processor	Microgrid	[10]
Human-Machine Interface	Energy storage system	Auxiliary energy storage units	Energy storage device	[11]
Prediction control	Energy storage system	Monitoring device	Energy storage device	[12]
Temperature Control using composite catalyst	Energy storage system	Fuel Cell	Hybrid Materials	[13]
Power Control using MOSFETs	Electrolysis System	Fuel Cell	Hydrogen Generation	[14]
Electronic control	electrolyser System	Electrolytic cell	Hydrogen Generation	[15]
Regulate gas compression power	Energy storage system	Compressor	Electricity Generation	[16]
Flow Control/ Power consumption control	Energy storage system	Compressor	Grid	[17]
Downstream process	Compression system	Compressor	Electricity Generation	[18]
Ultralow voltage DC (ULVDC) Power control	Power control system	Feed header	Hydrogen Generation Plant	[19]
Pressure Control	Energy storage system	Pump	Hydrogen production module	[20]
Electrode separated by Hydrogel membrane	Electrolysis system	electrolyser cell	Hydrogen Generation	[21]
Hydrogen supervisory control	Data acquisition system	Hydrogen tank	MEGC trailer	[22]
Flow control module	Hydrogen production system	Large-flow hydrogen-rich water preparation equipment	Agricultural planting	[23]
Self- Healing Electrodes	Electrolysis system	Electrocatalytic wastewater electrodes	Hydrogen Generation	[24]
Thermally conductive network	Hydrogen storage system	Heater	Hydrogen Storage	[25]
Temperature control using heat transfer medium	Hydrogen production system	Cooling device	Hydrogen Generation	[26]
Pressure regulation	PEM water electrolyser system	Water electrolyser cell	Hydrogen Generation	[27]
Nanoparticles electrode	Hydrogen production system	Electrolyser	Hydrogen Generation	[28]
Communication network	Fleet management system	Electric vehicle component	Vehicle-to-grid energy	[29]
Estimating electrical properties	Data processing system	Electrolyser	Electrolyser	[30]
Harmonic filters	Power electronic system	Electrolysis cells	Hydrogen Generation	[31]
Pulse width modulation	Electrolysis system	Electrolysis cells	Hydrogen Generation	[32]
Pressure regulation	Hydrogen production system	Electrochemical cell	Hydrogen Generation	[33]
Supply nominal energy	Hydrogen production system	Liquefier	Liquid hydrogen production	[34]
Charge regulator	Charge control unit	Electronic devices	Grid scale electricity storage	[35]
Temperature sensor	Hydrogen production system	High temperature Electrolyser	Thermal energy storage	[36]
Regulate a methanol inlet	Reactor system	Temperature control valve	Methanol production	[37]
Regulate flow using valve	Hydrogen production system	Compressor Modules	Large-Scale Hydrogen Refueling Station	[38]
Homogenizing the degradation	Hydrogen production system	Electrolyser	electrolyser plant	[39]
Controlling cooling power	Refrigeration system	Thermal expansion valve	Refueling containers	[40]
Communicate electromagnetic energy	Energy storage system	Coil device	Hybrid vehicle	[41]
Pressure regulating valve	Pressure compensating system	electrolyser stack	Hydrogen Generation	[42]
Optimize frequency tank profile	Cooling system	Cooling bank	Hydrogen refueling station	[43]
Configured to receive electrical power	Hybrid system	Cell	Electricity grid	[44]
Remote monitoring and reprogramming	Remotely reprogrammable system	Robotic arm	Robotics	[45]
Regulate thermoneutral voltage	Thermal management system	Electrochemical cell	Electrochemical cell	[46]
Hydrogen leakage detector	Fuel cell system	Electrochemical cell	Fuel cell	[47]
Wind power regulation	Energy storage monitoring system	Electrolyser	Wind power generator	[48]
Stabilize hydrogen production using evaporimeter	Mellow wine mixed fuel -power system	Electrolyser	Gasoline car	[50]

Station, a plurality of compressor modules comprising a local controller being used to facilitate control of valve [38]. Model predictive control [5] and time-dependent predicted optimization [6] are two techniques for controlling renewable energy sources that are patented by Air Products and Chemicals Inc. A control system for a microgrid application is patented, under the control of a processor using programmable logic controller (PLC), to receive signals from the said in-situ diagnostic means to determine performance parameters linked with a plurality of electrolyser [10]. Airbus, the patent owner, has implemented an energy management system where the controller is configured to operate each of the at least one electrical load, i.e., electrical load management control has been installed such that the minimum load to the fuel cell is ensured to run at optimal efficiency [9].

Several inventors also utilized specific methods to enhance fuel cell performance including controlling temperature with composite catalyst [13] and controlling power using metal oxide semiconductor field-effect transistors (MOSFETs) [14]. Cancellieri Franco has claimed to implement an electronic controller for an electrolytic cell [15], while others have patented harmonic filters and [31] and, pulse width modulation [32]. Wright Martin and Fraenkel Peter claims on the energy storage system features a control system for regulating cooperative or complementary performance of the first and second subsystems of the external power system network [7]. The invention of Vikoren and Bech pertains to a hydrogen supervisory control and data collecting system for monitoring numerous batches of hydrogen [22]. Henrik and Karsten patented a control system in which the movement of a flexible part is monitored by a sensor system and its signals are utilized by an automated control system to regulate oxygen flow out of the electrolysis

system [8]. Damon et al. have patented a control system that employs human machine interface (HMI) and is accessible through a web platform to enable comprehensive monitoring and automation, comprising self-regulation of the energy storage device and control of the device's functioning [11]. Yousif and Robert have patented a control system for an energy storage system that uses prediction control to monitor devices. A hydrogen production plant in accordance with the applicant's claim comprises an ultra-low voltage direct current (ULVDC) power control system electrically connected to receive the energy and designed to supply a regulated output to the electrolysis system [12].

One inventor invented a process for producing hydrogen from water in a solid/semi-solid state using a hydrogel membrane [21], while another developed a method for generating hydrogen by applying voltage to an electrode containing nanoparticles [28] and one more patented generating hydrogen from wastewater using self-healing electrodes [24]. The patent mentioned on the apparatus for estimating electrical properties of an electrolyser comprises a data processing system for estimating electrical values [30]. Pressure plays a crucial part in the generation of hydrogen. For the effective functioning of the electrolyser, the inventors used several pressure control methods. One inventor used a pressure control on a water-pressurizing pump to ease the pressurization of hydrogen and oxygen generated by electrolysis [20]. Another method used in the patent where the cathode compartment is operated at a pressure between 0.5 bar and 35 bar higher than the anode compartment [27]. One inventor used pressure control on the membrane electrode assembly (MEA) of the water electrolyser cell [33], while another inventor utilized pressure regulation on the pressure compensating system for a dual fluid flow system [42]. A method for making an electrolysis plant operate at its highest yield point while homogenizing the degradation of the Electrolyser, including the stages of acquiring data on the electrical consumption, temperature, voltage, and hydrogen generation of each electrolyser cell throughout the complete current range [39]. Hydrogen pressure is regulated by the flow control module in large-flow hydrogen-rich water preparation equipment for agricultural planting [23]. An approach to generating hydrogen was patented by Luke et al., and it involves heating the thermally conducting network using the heater in order to release hydrogen gas from a hydrogen storage device [25].

To control and/or regulate the temperature of the water fed to the ion exchanger to the PEM electrolyser, the patented technique of the inventor employs a cooling device through which the flow of the heat transfer medium is carefully controlled, either completely, partially, or not at all [26]. An inventor has patented a computer-implemented method for controlling multiple vehicles, such as electric and hydrogen vehicles, which involves communicating with multiple hydrogen providers over a communication network to identify hydrogen supply parameters associated with a hydrogen market and then analyzing those parameters to determine a hydrogen supply associated with that market [29]. In the patented method initiated by Laurent et al., the electronic controller is programmed to provide power to the liquefier at a predetermined nominal electrical energy level [34]. To store electrical energy, Marten and Bernhard developed an energy apparatus that supplies the cell with an aqueous liquid and electrical power from an external power source to the electrically charged functional unit, with the functional unit being charged at a potential difference between the cell electrode and the external power source of more than 1.37 V during at least part of the charging time [35]. Raghavan et al. created a technique where a control unit of the hydrogen production system is connected to a thermal energy storage temperature sensor, which transmits signals when a predetermined threshold temperature value is reached to cease charging or start heat discharging [36]. Method invented by Laura et al. includes a valve configured to regulate methanol inlet into the inlet stream based on information received from the temperature controller [37]. Jacob et al. patent a method for optimizing hydrogen refueling station control based on the tank's high-frequency profile [43]. The manufacturing process for hydrogen is stabilized, and exhaust pollution from gasoline vehicles is greatly reduced as stated in the patent own by Guangxi Qiming Hydrogen Energy Co LTD for a system in which an evaporimeter is connected to the end of the pipeline of the inner chamber and the other end is connected to an electrolyser [50].

The electrolyser control system for the hydrogen production patents has been utilized in numerous types of the system in various applications. Fig. 18 shows that the graph provides a visual representation of the frequency of various hydrogen energy production systems over a five-year period. The figure shows the frequency of various systems connected to the production of hydrogen energy, with larger letter sizes representing more occurrences and smaller letter sizes representing fewer occurrences. The rising popularity of energy storage systems demonstrates their importance in managing intermittent renewable energy sources and ensuring a stable energy supply. The wide use of hydrogen production systems reflects the significance of producing hydrogen as a clean and sustainable fuel via electrolysis and reforming. A significant number of electrolyser systems play a crucial role in the electrolysis process, in which water splits into hydrogen and oxygen using electricity. The widespread usage of compression systems indicates their importance in increasing hydrogen density for efficient storage and transport. Renewable energy systems indicate a growing emphasis on producing hydrogen from renewable energy sources. The integration of numerous auxiliary systems such as refrigeration, data acquisition, and energy management highlight the complexity of hydrogen energy production and the need for integrated technologies and processes. Overall, the figure portrays the technical aspects and interplay of various systems involved in the production of hydrogen energy.

Table 2 represents the control system used in the last 5 years for the electrolyser control technology for hydrogen production. All this control system has been classified into specific category including temperature, pressure, power, flow, and communication in Fig. 19. It can be seen from the figure that the majority of the controller is in the enhancement of the power control followed by pressure control. Fig. 19 shows all the mentioned control method in the 107 patents where other patents have just discussed on the claim of the process but not on the specific control or method which all has been represented in Table 3.

5.2. Technology update on electrolyser-based hydrogen production application

Rapid technological advancements have positioned hydrogen as a globally viable alternative energy source. When used in fuel cells, hydrogen produces only water, energy, and heat, making it an environmentally friendly fuel. Its adaptability extends across various sectors, including transportation, commercial, industrial, residential, and portable applications, where it plays a vital role. The electrolyser, with its diverse applications, has seen an increase in patent activity in recent years, further driving the adoption of hydrogen fuel as a zero-emission solution. The reference is set from recent to older years, with [1] representing recent years beginning in 2022 and [107] representing past years beginning in 2002. Numerous industries employ electrolyser for the production of hydrogen, as seen in Table 4 shows significant improvements made by innovators to the control system of the electrolyser for hydrogen generation in various industries. Hydrogen can be generated from a variety of local resources. Most of the hydrogen is now generated from fossil fuels, particularly natural gas. Currently, electricity derived from the grid or renewable sources such as wind, solar, geothermal, or biomass is also used to produce hydrogen. Solar energy and wind energy have only been mentioned in the patent to produce hydrogen. Based on the data in Table 3, it is apparent that solar energy is the most recently patented renewable energy source. It is noticeable that fuel cells in electrochemical cells are the favored method of producing hydrogen, as opposed to electrolysis cells. Hydrogen can be stored in either its gaseous or liquid phase. When compared to liquid storage, gaseous hydrogen requires specially designed, high-pressure containers

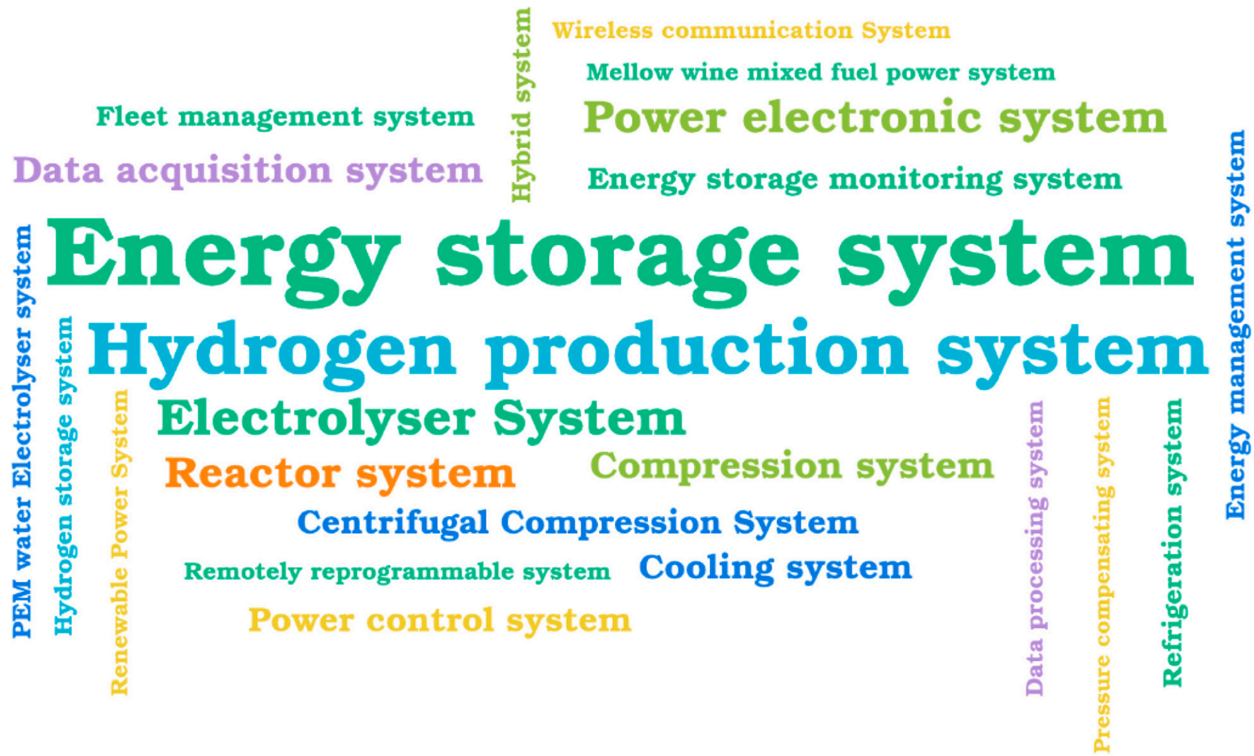

Fig. 18. Frequency Analysis for system utilized in H_2 Production in the patent over last 5 years.

Fig. 19. The control methods used in the patent in recent 5 years.

Table 3
The hydrogen's patent-referenced application.

Category	Application		Patent Documents
Hydrogen Source	Renewable Energy	Wind	[39,48,62,63,72,75,81,82,87,91,93,94,103,105]
		Solar	[20,53,56,62,63,72,79,80,94,103,105]
Hydrogen Production	Electrochemical cell	Fuel Cell	[9,13–15,24,33,46,47,52,55,58,60–62,65,67,68,73,78,79,85,87,89,98–101,103,104,106,107]
	Electrolysis cell		[8,19–21,24,26,31,32,49,52,76]
Hydrogen Storage	Energy Storage	H_2 gas storage	[3,7,33,42,74,83,89,97,100,102]
		H_2 liquid storage	[18,34,79,81,88,95,97,106]
		Gravity storage technology	[7]
		Thermal energy storage	[25,36,71]
Hydrogen Transportation	Hydrogen tank	Liquid hydrogen tank	[34,79]
		Gaseous hydrogen tank	[38,40,43]
		Multiple Element gas container (MEGC) Trailer	[22]
Energy Conversion	Electrolyser	Polymer electrolyte membrane or Proton-exchange membranes (PEM)	[13,21,22,26–28,31,36,38,53,59,60,70,79,88,103,104,107]
		Anion exchange membrane (AEM)	[1,8,10,11,22,33,35,36,38]
		Solid oxide fuel cell	[69,77,85,88,103,104]
		Alkaline water	[62,63,70,88,103,104]
		Molten carbonate fuel cell	[97,104]
		Regenerative fuel cell	[97]
		Zinc-air fuel cell	[97]
		Protonic ceramic fuel cell	[97]
		Phosphoric acid fuel cell	[97,104]
Hydrogen consumption	Transport	Automobile	[4,29,41,50,55,64,65,74,77,80,83,89,98,103,106]
		Aerospace	[9,56,104]
	Power Station	Microgrid	[1,10,96]
		Grid	[16–18,29,35,44,71,72,75,81,82,84,86,88,94,96,98,99,103,105]
		Industrial Power Plant	[5,6,70]
		Nuclear Power Plant	[88,96,103]
	Industry	Agriculture	[23]
		Methanol Production	[37]
		Advanced Materials	[13,24,49,51,59,60,66,80,83,85,90,107]
		Robotics	[45,70]

Table 4
The standard comparison of the electrolyser used in the patents by manufacturer.

	PEM	AEM	ALK
Manufacturer	Nel Hydrogen	Enapter	Nel Hydrogen
Model	C-Series	EL4.0	A-Series
Patent Reference	[38,43]	[1,10,33]	[38,43]
Technology Status	Commercial	Commercial	Commercial
Production Rate	10–30 Nm^3/h	0.5 Nm^3/h	50–3880 Nm^3/h
Operative Temperature Range	5–40 °C	5–50 °C	5–35 °C
Pressure	1–4.1 barg	8–35 barg	1–200 barg
Energy Consumption of H_2	5.8–6.2 kWh/Nm^3	4.4kWh/Nm^3	3.8–4.4 kWh/Nm^3
Water Consumption	9–26.9 L/h	420 mL/h (25 °C)	–
Power Consumption	85-256 kW	2.4–3 kW	–
Control system	-Automatic Fault detection -Remote Communication —H_2 Leakage Detector	-Fully Automatic EMS via Bluetooth and Wi-Fi -Data communication via PLC	- Optimized frequency tank profile for the cooling bank
Advantage	- Less water consumption - High H_2 purity	- Low cost - Compact cell design	- Low initial cost - High H_2 pressure
Disadvantage	- Low pressure - High power consumption	- High water consumption - Low production rate of H_2	- Low ion conductivity - Low thermostability

* PEM-Polymer electrolyte membrane or Proton-exchange membranes; AEM-Anion exchange membrane; ALK-Alkaline water.

[38].

Hydrogen gas storage has been widely discussed in recently granted patents. The patent also refers to two additional technologies: gravity storage and thermal energy storage. Hydrogen requires extensive logistics to be utilized on a global scale. It is essential to keep its focus on safety during the transport process. Hydrogen may be transported more effectively if it is converted to a liquid form. While hydrogen gas has a lower density than liquid hydrogen, the latter has a far greater energy density. Thus, the same amount of space may be used to convey far more liquid hydrogen than gaseous hydrogen [34]. Two patents mentioned transporting hydrogen in liquid state and 3 in gaseous form. Additional patent discussed on transporting hydrogen in multiple element gas container (MEGC). With the use of an electrolyser, hydrogen is transformed into electrical energy. The patent makes a highlight of a variety of distinctive electrolyser types, including polymer electrolyte membrane (PEM) electrolyzers, anion exchange membrane electrolyzers, solid oxide fuel cell electrolyzers, alkaline water electrolyzers, and regenerative fuel cell electrolyzers. Further, fuel cell technologies such protonic ceramic fuel cells, molten carbonate fuel cells, zinc-air fuel cells, and phosphoric acid fuel cells are also featured. It is essential to acknowledge that although fuel cells are different technologies that use hydrogen to produce energy, electrolyzers are devices used for the electrolysis process of producing hydrogen. PEM appears to be the most prominent electrolyser among them, with AEM coming in second as can be observed from Table 3. It is also noteworthy from Table 3 that the recent development of the AEM control system accounted from patent activity as per reflection from the referencing. Wide-ranging applications use hydrogen, specifically those that are approaching close to achieving the zero-emission policy. According to Table 4, the grid and automobile technologies are being employed significantly in the development of control systems for electrolyser. It is evident that the primary sources of carbon emissions are the transportation and power generation sectors, hence measures to reduce carbon footprint are being considered.

Based on the information in Table 4, the control system for electrolyser in microgrids and aircraft has recently been patented. Many fields are finding uses for hydrogen, and new technologies are being developed by innovators to optimize its potential.

Fig. 20 shows the detailed infographic of the application technology update for the electrolyser control technology for hydrogen production. Fig. 20 has been provided with top application and process flow of hydrogen as pie chart and supported with bar chart for the number of patents in the specific application. It can be observed from Fig. 20 that the majority of the application is used for fuel cell of 28.4 % patents followed by renewable energy which has been categorized into bar chart into wind and solar where wind dominates over solar for hydrogen source. For hydrogen process flow it can be seen that the majority of the patents have been filed on hydrogen production followed by conversion, consumption, source and finally storage.

5.3. Technology update by specific owner of the patent

It is important to understand who is responsible for the technological update of the electrolyser control for hydrogen production. A variety of technology has recently been claimed by various patent owners. The most recent five years of patent owners have been filtered to highlight those who have been actively patenting their inventions in recent times based on the analysis of data from 107 patent. Fig. 21 shows the recent 5 years patent owners who have owned the invention between 2018 and 2022. As the graph indicates, there has been a surge in patent publications in 2022 from a wide variety of owners, indicating that demand for hydrogen is on the rise. Several owners appear to have published numerous patents over the period of our five-year evaluation. Four patents that included the claiming of control systems in compressors and hardware processors were published in 2022 by Air Products and Chemical Inc. For the enhanced hydrogen production, they used four distinct technologies, including the centrifugal compressor stage [3], downstream process [18], model predictive control [5], and time dependent predictive optimization [6], which they claimed in four individual patents. Air Liquide claimed three distinct technology for power control in the year 2020 and 2021. One of the claim includes control of cooling power of the refrigeration system [40], followed by claiming on method used in the power electronic system employing harmonic filters [31] and, last one on the supply of nominal energy for liquefier [34].

Contrarily, in 2021 and 2022, Enapter also filed for three patents. They claimed method on the pressure regulation for electrochemical cell [33], followed by claiming a method using mesh network control [1], and receive signals from the said in-situ diagnostic means [10] for the Microgrid application. Nel Hydrogen patented 2 papers in the year 2019 and 2020. They claimed the method of optimizing the frequency tank profile of the cooling bank [43], and to regulate flow using the valve of compressor modules [38]. Furthermore, in 2022, Woodside Energy Technologies Pty Ltd. also filed for two patents including claiming method on pressure control of the pump [20], and ULVDC power control of the feed header [19]. Honda Motor Co Ltd. and Airbus two of the

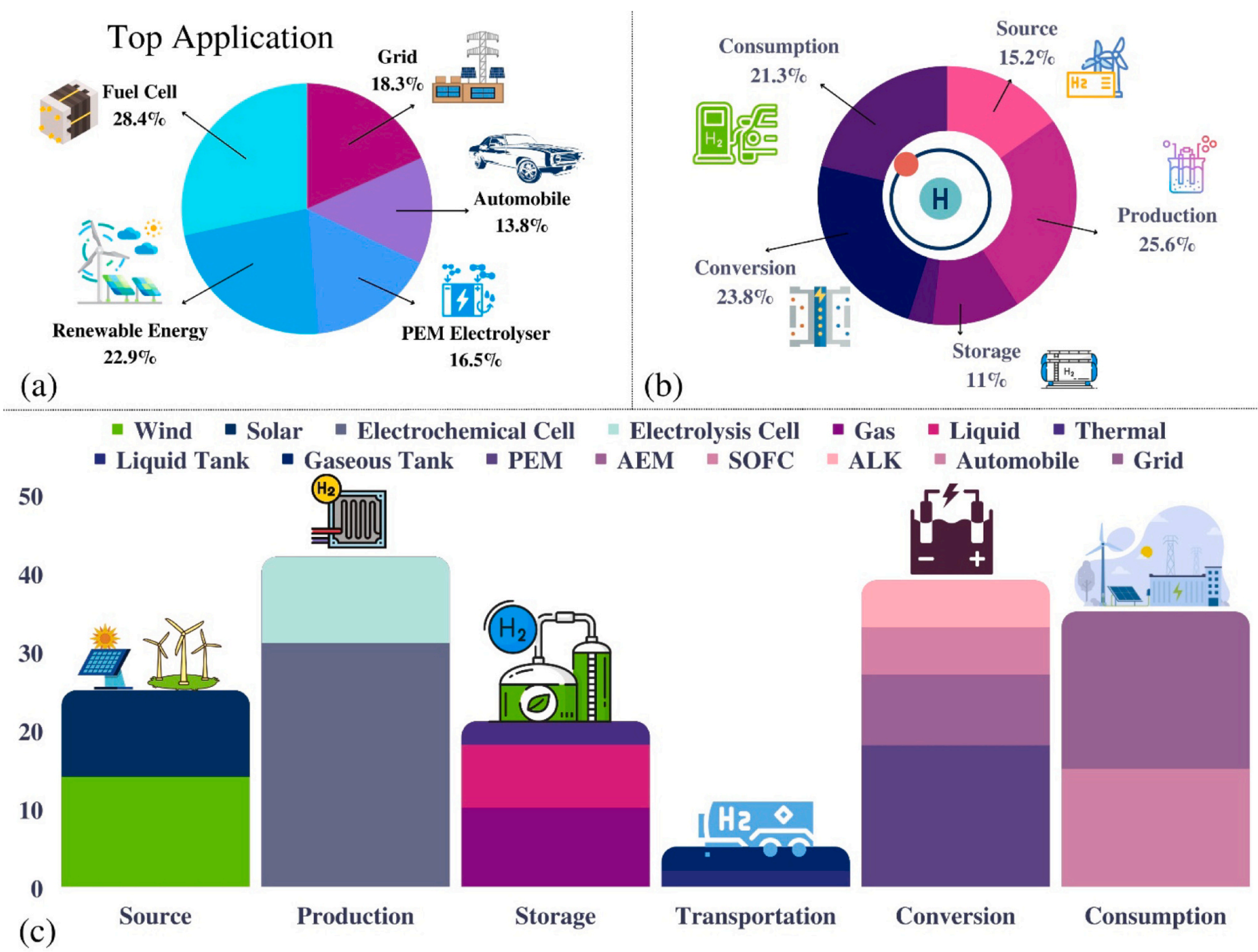

Fig. 20. Application of the electrolyser technologies for hydrogen production patents in recent 5 years (a) top 5 applications of fuel cell, renewable energy, grid-connected, automobile and PEM electrolyser (b) hydrogen process in terms of production, conversion, consumption, source and storage (c) top applications in specific category.

Fig. 21. The electrolyser control technology update by owner in last 5 years.

popular company in the transportation sector has also patented claiming method on communication network for electric vehicle component by Honda in 2021 [29], and electrical load management control for electric motor by Airbus in 2022 [9]. Several universities have filed patents on the electrolyser control system, that is used in the production of hydrogen. These include the Delft University of Technology for "power control" for a hybrid system [44], LUT University for "estimation of electrical properties" for a data processing system [30], Oxford University Innovation Ltd. for "method of using nanoparticles electrode" for an electrolyser [28], and the University of Birmingham for "prediction control" of a monitoring device [12]. Similarly, several patent holders have updated the control system of their electrolyser, improved its

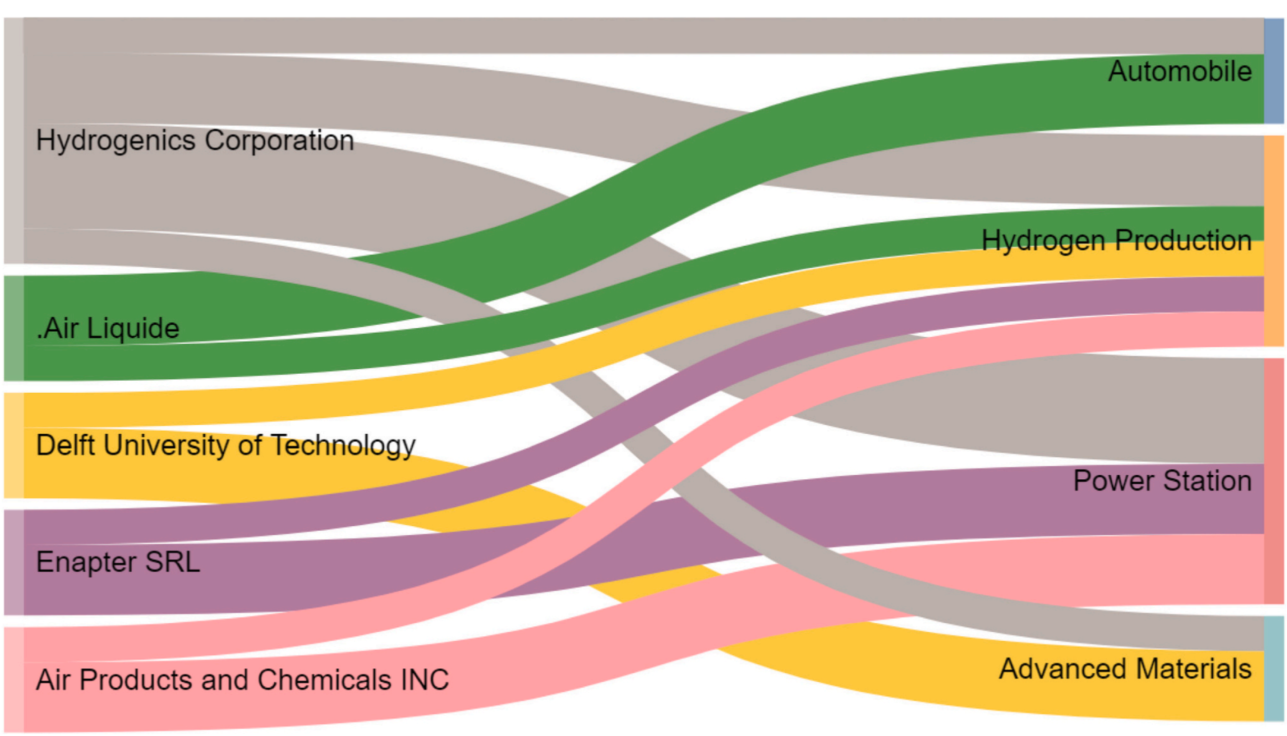

Fig. 22. The top 5 applicant technology contribution in specific sectors.

performance and reduced energy consumption, to take advantage of the latest technological advancements in this field.

In Fig. 22, it is represented that the top 5 applicants who have filed patents in specific sector or application. The majority of the patents have filed by Hydrogenics Corporation under category of automobile, hydrogen production, power station, and advanced materials.

Likewise, Air Liquide [34], Enapter [33], Technische Universiteit Delft [35] and Air Production & Chemicals [18] are in the top 5 list for the filing of the patent in automobile, hydrogen production, power station, and advanced materials. It is observed that most of the applicants filed patents in power station applications followed by hydrogen production and so on.

6. Technical comparison of different types of electrolyser technologies

The advancement of electrolyser control technology is reliant on patent publishing trends and the evolution of distinct control system development techniques, which are unique due to differences in the research focus, inventor methods, and research gap necessities. Moreover, the emphasis on patents might vary according to a variety of challenges and issues. In this part, a technical comparative study of

Table 5
The alternative control method for electrolyser of the selected patents.

Category	Control Method	Controller/ Method	Advantage	Disadvantage
Temperature	Thermally Conductive Network	- Thermal conductive fillers - Thermally Conductive Foams	Good thermal stability Low cost	Reduce mechanical property
	Composite Catalyst	- Carbon doped nitrogen - Carbon based platinum nanoparticles - Non-precious transition metal	Decrease the temperature gradient across the porous	Expensive process
	Temperature Sensor	- Thermocouples - RTDs - Thermistors	Reliable and accurate	Low sensitive to small temperature changes
Pressure	Centrifugal Compressor Network	- Proportional integral derivative (PID) control - Anti surge controller	Suitable for continuous compressed air	Unsuitable for very high compression
	Downstream Process	- Separation of particles - Extraction - Concentration - Purification	Reduce the pressure of said compressed H_2 gas	Expensive method
	Mass Flow Controller	- Proportional integral derivative (PID) control	Automatically controls the flow rate of a gas according to a set flow rate sent	Not accurate when measuring wet gas.
	Pressure Sensor	- Aneroid barometer - Manometer - Bourdon tube - Piezoelectric	Good reliability	Temperature sensitivity
Power	Harmonic Filters	- Passive - Active - Hybrid filters	Fast response to varying load	Expensive complex method
	Model Predictive Control (MPC)	Advanced control methods	Multivariable controller that controls the outputs simultaneously	Several MPC models are limited to only stable, open-loop processes
	Charge Regulator	- Shunt type - Series type - Pulse-width modulation - MPPT	Improve charging efficiency	Shorter lifespan due to complex electronic components
	Cooperative control	- Optimal Control - Adaptive control	Build extended and flexible loads	Complex method to design centralized control
	MOSFET	- PMOS Logic - NMOS Logic - CMOS Logic - DMOS	Low gate losses Voltage controlled device	Unipolar voltage device
	Evaporimeter	Measure - evaporation rate from a free water surface - continuously wet porous surface.	Easy observation Low cost	Effects of wind and radiation causes overestimation of the expiration rate
	Hydrogen Leak Detector	Semiconductor type gas sensor	Low cost gas sensor	Cannot detect sonic range noises
Flow	Flow Control Valve	- Gate valve - Globe Valve - Pinch Valve - Diaphragm valves	Help maintaining a constant calibrated flow rate	Prone to leakage when operated at high temperatures
	Discharge Valve	- Upward exhibition - Downward exhibition	Avoid back pressure	Expensive
Communication	Mesh Network Control	- Wi-Fi mesh network - Wired mesh network - Hybrid mesh network	Scalability is simple	Expensive and complex structure
	Communication Network	- Wheel network - Chain network - Circle network - All-channel network.	Convenient Sharing of Resources	More open to interference
	Human Machine Interface	- Pushbutton replacer - Data handler - Overseer	Improved Productivity	Complex design

* RTDs- Resistance temperature detectors; ULDVC- Ultralow voltage direct current; MOSFET- Power Control using Metal oxide semiconductor field-effect transistors.

patent papers published in the previous five years by various patent owners has been discussed. Before going to the technical comparison of the electrolyser control technology, a brief comparison of the existing electrolyser has been discussed in Table 4. The comparison of the three of the most used electrolyser as per Table 4 has been presented in Table 4. The evaluation data has been extracted from the owners of the patent including Nel Hydrogen for PEM and Alkaline water, and Enapter for AEM electrolyser. Various important technical data has been represented in the table where the control system, advantages and disadvantages have been stated. Different electrolyzers have been designed in a way for specific application where the efficiency wise it can be observed that Alkaline water electrolyser is in the top but consist of limitation in operative temperature range.

Table 5 represents the comparative information on the advantage and disadvantage of the different control method used in the patent as per Fig. 19. The patent owner of the 107 selected patents has filed information on the pros and cons of the technology or control method they have used which all has been extracted and represented accordingly in Table 5.

7. Conclusion and recommendation

Recent years have seen significant development in hydrogen technology. Owners, applicants, and inventors have benefited greatly from the patent analysis described in this article when establishing strategic goals for the growth and commercialization of new technologies. The United States and Europe have long been at the forefront of technological innovation. The findings of the patent landscape, however, show that Russia, China, Romania, and Spain are also the leaders when it comes to the design of innovative electrolyser control system for hydrogen production. As we strive to achieve the zero-emissions targets, monitoring patent filings may reveal which jurisdiction and organizations inside those nations are making headway in developing methods to utilize this energy resource. Hydrogen technology has the potential to play a pivotal part in the global energy revolution, and water electrolysis is a key enabling chemical process for this to happen. Several energy-intensive industries and sectors may be decarbonized with the help of hydrogen technology, particularly if hydrogen production is run on renewable energy. In this light, electrolyser have emerged as a critical enabler of the transition to a hydrogen-based energy infrastructure. This research delves into the numbers and patterns of patent applications pertaining to electrolyser, highlighting the many elements and components that are gaining more focus. Electrolyser control technology for hydrogen generation is analyzed in this study using a patent landscape analysis to assess the current state of the patent landscape in this area. The benefits of conducting a patent landscape analysis include the following:

- Identifying emerging technologies and market trends.
- Generating insights on the competitive market for R&D-intensive fields.
- Classifying inventor networks and information interactions among industries.
- Associating the growth of technical sub-sectors.
- Locating study areas that have been explored.

A closer look at the patent data reveals five developing patterns in areas where technical innovation is required to improve electrolyser efficiency and lower costs. To begin with the most effective means of producing hydrogen are being explored, including the finest possible operating conditions and electrolyser design. Second, the increase in patents for non-noble metal electrocatalysts shows that research and development are shifting towards discovering new solutions and trying to minimize the impact of material scarcity. Third, polymer separator membranes are becoming a hotbed of patent activity as researchers seek to improve both technical performance and durability at the same time. About 5 % of patent applications, on average, specifically address improved longevity or durability. Fourth, there has been an uptick in patenting activity related to the control method of electrolyser and, more recently, with AEM electrolyser. This is all part of an endeavor to boost the efficient and cost-effective generation of hydrogen on a larger scale. Finally, renewable energy or more precisely solar energy is a promising new field in patenting, and researchers at institutions all around the globe are working intensively towards developing innovative methods for producing hydrogen and oxygen from water using just the energy contained in sunlight. The study's aim is to assist scientists and technologists in better understanding the impact and developments of electrolyser control technologies for hydrogen production by providing them with a better understanding of current trends in research and patenting. Initial steps in evaluating the present status of electrolyser control methods for hydrogen generation include a thorough analysis of the Lens database and the selection of 107 patent papers significant to the subject. This article evaluates the patent based on electrolyser control technologies for hydrogen production using analytical and technological methods. An overview of the market's major competitors, growth rates, and CPC-coded patent categorization are all part of the bibliometric study. The technical study offers an assessment of innovations, a classification of inventions to address problems in the area of electrolyser control technologies for hydrogen generation, an analysis of technological trends, and a cross-jurisdictional study of the patent landscape.

Several limitations exist in the progress of electrolyser technology that hinder its widespread adoption and advancement. These limitations include:

- High costs concerned with electrolyser technology.
- Limited robustness due to corrosive electrolytes and high operating temperatures.
- Challenges in scaling up production to meet larger hydrogen demand.
- Require improvements in energy efficiency of electrolyser systems.

Future advancements in electrolyser technology can be accomplished by concentrating on strategies for cost reduction, enhancing durability through material advancements, scaling up production methods, enhancing energy efficiency, and conducting research into novel materials and catalysts. By addressing these issues, electrolyser technology can become more economically viable, dependable, scalable, energy-efficient, and technologically advanced, paving the way for widespread adoption and use of hydrogen as a clean and sustainable energy source. The remarkable growth in electrolyser is anticipated to persist and stimulate further innovation. There is a compelling need for technical approaches to lower the cost of production of hydrogen while simultaneously increasing technical efficiency and manufacturing capacity, and the growing trend in patent applications suggests that more innovations will come shortly to meet this demand. Increasing the efficiency and sustainability of hydrogen generation via technological innovation in electrolyser is seen as a promising path towards meeting the needs of a rapidly expanding range of applications, including decarbonization and accelerating the energy transition progress.

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.

Data availability

No data was used for the research described in the article.

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