GLOBAL TRENDS ON TECHNOLOGIES USED FOR THE RENEWABLE HYDROGEN PRODUCTION

TENDÊNCIAS GLOBAIS SOBRE TECNOLOGIAS UTILIZADAS PARA A PRODUÇÃO DE HIDROGÊNIO RENOVÁVEL

Daniel de Cerqueira Lima e Penalva Santos[a], Yana Amaral Alves[b], Kátia Ferreira de Oliveira[c], Maísa Danielle Lins de Sousa[a], Cristina Gomes Souza[c], Ronney Arismel Mancebo Boloy[c]

[a]Instituto Federal de Educação, Ciência e Tecnologia de Pernambuco (IFPE), [b]Instituto Arapuá, Departamento de Pesquisa, [c]Cefet/RJ - Centro Federal de Educação Tecnológica. Programa de Pós-graduação em Engenharia de Produção e Sistemas

daniel.penalva@cabo.ifpe.edu.br, yana.amaral@hotmail.com, katia90feroli@gmail.com, maisaalins18@gmail.com, crisgsouza3@gmail.com, ronney.boloy@cefet-rj.br

Submissão: 02 de fevereiro de 2025   Aceitação: 18 de junho de 2025

Abstract

Due to the damage caused by fossil fuels, hydrogen emerged as an alternative to producing cleaner energy using different technologies and raw materials. Most of its production is still carried out, emitting large amounts of greenhouse gases even though several alternatives are for their replacement. This article analyzes renewable hydrogen production considering its production from organic waste, biomass, and water electrolysis using solar and wind energy through quantitative and qualitative approaches of Scientific Articles and Reviews, Patent Documents, and Institutional Documents. The main results show that China and the USA are the most significant power in the development of technologies and target markets. Chinese technology developers are more closely linked to State Research Institutes and universities than private companies, an inverse profile observed in the USA. Japan, Canada, Australia, and European countries such as Germany stand out as developers and even more interesting markets. South Korea presents an outstanding performance supported by public-private partnerships. Developing countries such as Brazil, India, and Taiwan show little local technological development but awaken interest in protection from other countries. There is a migration of areas of interest, both from large industries from different sectors and non-renewable energy industries to renewable hydrogen. Water electrolysis is the most common way to produce biohydrogen using solar and wind energy as a source. Thus, this research highlighted, in addition to the current situation of hydrogen production from renewable sources, prospects for technological and commercial routes between countries and organizations that are at the forefront of innovations in this market.

Keywords: renewable energy; hydrogen market; innovation; patent.

Resumo

Devido aos danos causados pelos combustíveis fósseis, o hidrogênio surgiu como uma alternativa para a produção de energia mais limpa, utilizando diferentes tecnologias e matérias-primas. A maior parte de sua produção ainda é realizada emitindo-se grandes quantidades de gases de efeito estufa, embora existam diversas alternativas para sua substituição. Este artigo analisa a produção de hidrogênio renovável considerando sua produção a partir de resíduos orgânicos, biomassa e eletrólise da água, utilizando energia solar e eólica por meio de abordagens quantitativas e qualitativas de artigos e resenhas científicas, documentos de patentes e documentos institucionais. Os principais resultados mostram que a China e os EUA são as potências mais significativas no desenvolvimento de tecnologias e mercados-alvo. Os desenvolvedores de tecnologia chineses estão mais intimamente ligados a institutos de pesquisa estatais e universidades do que a empresas privadas, um perfil inverso observado nos EUA. Japão, Canadá, Austrália e países europeus como a Alemanha se destacam como desenvolvedores e mercados ainda mais interessantes. A Coreia do Sul apresenta um desempenho notável apoiado em parcerias público-privadas. Países em desenvolvimento como Brasil, Índia e Taiwan apresentam pouco desenvolvimento tecnológico local, mas despertam interesse na proteção de outros países. Há uma migração de áreas de interesse, tanto de grandes indústrias de diversos setores como de indústrias de energia não renovável para o hidrogênio renovável. A eletrólise da água é a forma mais comum de produzir biohidrogênio usando energia solar e eólica como fonte. Desta forma, esta pesquisa evidenciou, além da conjuntura atual da produção de hidrogênio a partir de fontes renováveis, prospecções de rotas tecnológicas e comerciais entre países e organizações que estão na vanguarda das inovações deste mercado.

Palavras-chave: energias renováveis; mercado do hidrogênio; inovação; patente.

1 INTRODUCTION

The development of humanity is directly linked to the discoveries of different energy sources. Thus, to replace fossil fuels and reduce the emission of greenhouse gases, hydrogen emerged as an alternative to clean energy, capable of being implemented to expand the global energy matrix and also to be used as fuel in electric cars (Kamaraj; Ramachandran; Aravind, 2020).

Hydrogen is the most abundant element in the universe, but it is rarely found in its elemental form in nature. It can be classified according to its source and form of production and can be obtained through raw materials that emit polluting gases, such as coal, methanol, and nuclear energy, or through renewable sources, such as solar, wind, organic waste, and water (Baykara, 2018; Arruda *et al*., 2025). Even though 96% of the world's hydrogen production is still made from fossil compounds, renewable hydrogen is already known as the "fuel of the future", as it has high energy efficiency, low environmental impact, and economically viable production (Dincer, 2012; Ursúa; Gandía; Sanchis, 2012; Baykara, 2018; Lukajtis *et al*., 2018; Anand *et al*., 2025).

However, improvements in hydrogen production costs need to be applied to increase competitiveness in the current market and promote decentralized energy production, taking advantage of the resources of each region, using cocatalysts with non-noble metals or with photoelectrodes with oxide materials low cost or with new solutions (Bak *et al*., 2002; Holladay *et al*., 2009; Luo *et al*., 2014; Zou; Zhang, 2015). Despite this, with the public policies applied and with the targets for decarbonization in several countries, hydrogen and hydrogen-based fuels will represent the second-largest final energy use in the economy by 2050, between 15-17% (Energy Transitions Commission, 2021). The European Union's objective is climate neutrality for 2050 and some countries in the bloc have national plans, such as Portugal with the "Carbon neutrality roadmap" (RNC 2050) focusing on hydrogen production; Germany with the "National H2" strategy and incentives for research and build related technologies; the Netherlands with a plan to transform provinces into "Hydrogen Valley", and others. The US has the "Hydrogen Program Plan" that promotes its production, transportation, storage, and use, and Morocco plans to build the first green hydrogen industry by 2025 (Energy Transitions Commission, 2021).

This work aims to analyze renewable hydrogen production considering its production from organic waste, biomass, and water electrolysis using solar and wind energy. In addition to a view over time and a current diagnosis, the identification of future opportunities and trends are determined by using Scientific Articles and Reviews (SAR), Patent Documents (PD) filed in the main patent offices in the world, and Institutional Documents (ID) from companies and governments that produce green hydrogen. This information was statistically treated for bibliometric and patentometric analysis, in addition to a qualitative deepening based on a systematic literature review on the Prisma method and content analysis of PD and reports.

2 HYDROGEN PRODUCTION

Hydrogen can be produced from various raw materials and in different ways and technologies (Dawood; Anda; Shafiullah, 2020; Anand *et al*., 2025). Much of the hydrogen production is still made from fossil fuels, but it can also be obtained sustainably through water, biological processes, fermentation and thermochemical processes (Dincer, 2012; Anand *et al*., 2025). This chapter describes some techniques for obtaining more environmentally friendly hydrogen.

2.1 Electrolysis

The production from the electrolysis of water occurs by the effect of the passage of an electric current in the liquid to dissociate it and promote the movement of electrons in an external circuit (Dincer, 2012; Li, 2025). Ursúa; Gandía; Sanchis (2012) carried out a study presenting the main foundations of this process and its technologies to conduct electrolysis: alkaline, polymer electrolyte membrane (PEM), and solid oxide electrolytes (SOEs). Through research, he concluded that the electrolyzes PEM and the alkaline are the only ones available commercially, but only the alkaline can produce a large amount of energy. SOEs are still in the research and development phase. Still, it can be seen to produce hydrogen using steam electrolysis at high temperatures and is also more expensive than other electrolyzes.

Chi and Yu (2018) also studied new technologies in this form of production. They demonstrated that nickel, iron, and cobalt materials could act as electrocatalysts in alkaline electrolysis and at a lower cost than using PEM. In addition, he explained that there are advantages in replacing proton exchange membranes with anion exchange membranes.

Zhang *et al*. (2021) highlights that, in addition to the high value of the electrode, the increased demand for energy is a bottleneck in the production of hydrogen by electrolysis of water, pointing out the addition of hydrocarbons as a solution to reduce energy consumption. It indicates a direction for research related to the use of cheaper electrodes or non-metallic composite materials, such as Ni, in addition to the use of the gas bubble exhaust method.

2.2 Bio-photolysis and photo-fermentation

The hydrogen production from bio-photolysis is a biochemical process that converts sunlight into chemical energy to dissociate water into hydrogen and oxygen with the help of biological converters, which are usually microalgae. Bio-photolysis can be classified as direct, indirect, or by photo-fermentation (Xie, 2024). The photo-fermentation process uses photosynthetic bacteria to determine the conversion of the substrate into hydrogen. However, it has some disadvantages, such as the high energy demand and well-designed anaerobic photobioreactors (Dincer, 2012; Nabgan *et al*., 2017).

In one study, Wu *et al*. (2016) used *Rhodopseudomonas* sp. nov. strain A7 and analyzed the feeding interval time, the initial feeding time, and the proportion of the feeding volume in the hydrogen production in a semi-continuous system in which a maximum hydrogen yield of 3.22 mol-H_2/mol was obtained as a result acetate and a light energy conversion efficiency of 1.9%. Guo *et al*. (2020) also studied this process by investigating the effects of the initial pH values of different phosphates acting as a buffer, and the result was that the phosphate worked better and had a maximum production of 569.6 mL of hydrogen with an initial pH of 6.0.

2.3 Dark fermentation

Different from photo-fermentation, dark fermentation is a process in which several microorganisms, in the absence of light, are used to hydrolyze carbohydrates and convert to hydrogen. The amount of hydrogen is not affected by any climatic conditions. It depends only on the pH value, the hydraulic retention time, the partial pressure in the gas, and the temperature. In one study, a maximum yield in hydrogen production of 88% and 49% was obtained in a batch and continuous process, respectively, using brewery effluent and sewage sludge as inoculum as substrate (Palanivel, 2025).

The pH in this process plays an important role and influences the metabolism of the substrate and the release of metabolic by-products. In addition to this parameter, the temperature can cause a 25% impact on production by increasing 5 ºC affecting the activity of hydrogen-producing bacteria (Vijaya Krishna *et al*., 2017).

Generally, dark fermentation is associated with a low yield and high productivity, while photo fermentation is associated with a high yield and low productivity (Zhang *et al*., 2021). Thus, dark fermentation / photo-fermentation technology is considered a new approach to increasing hydrogen yield and solid waste energy recovery (Zhang *et al*., 2021).

2.4 Gasification

Gasification is a thermochemical process that transforms 17% of the biomass weight into hydrogen. This process requires a large amount of energy and has low yields due to coal formation in the first stage resulting in less CO available for hydrogen production (Sarkar; Bhattacharyya, 2012). This production is affected depending on the type of biomass used, its concentration, the gasification temperature and the residence time. By increasing the concentration of the raw material, energy efficiency decreases, and the increase in temperature and residence time increases efficiency initially, which drops considerably afterward (Zhang *et al.*, 2019).

2.5 Steam reforming

Steam reforming is an endothermic equilibrium reaction, in which hydrogen is obtained through a catalyzed reaction between a hydrocarbon and steam (Martino *et al*., 2021). In this process they highlight steam reforming methane, bio-oil model molecules, methanol, and ethanol that can be easily obtained from renewable sources, highlighting steam reforming methane as the most viable route (Martino *et al*., 2021).

Hydrogen can also be produced by steam reforming or by oxygenated hydrocarbons. The fuel is injected into a reformer along with the superheated water vapor and the platinum-based catalyst (Levin; Chahine, 2010). Dou *et al*. (2014) studied the activity of the Ni-Cu-Al-based catalyst in the production from the reforming of the glycerol vapor in a fixed bed reactor of continuous flow under atmospheric pressure that increased the conversion of glycerol and the selectivity of hydrogen to raise the temperature that was in the range of 500-600 ºC.

Nabgan *et al*. (2017) analyzed the steam reforming process of phenol and acetic acid with the active metal catalysts Rh and Ni, supporting ZrO_2, La_2O_3 and CeO_2 using a fixed bed reactor. With these metals, it was possible to achieve a high level of hydrogen production, and the supports were considered adequate due to their basic character.

3 METHODOLOGY

Search strategies were developed in different sources and databases with a global reach to obtain scientific, technological, commercial, and political information on the production of green hydrogen, as per item 3.1. Then it was necessary to use quantitative and qualitative analysis methods, described in item 3.2, later allowing an integrated discussion of the main results from different perspectives.

3.1 Data collection

For the collection of information, 3 basic premises were taken into account: the source of information must be accurate and enable statistical and content analysis, the database must have global scope and reliability, and search strategies must be defined in such a way as to raise a set of documents dealing with the production of renewable hydrogen.

The primary sources of information used were the scientific article and reviews (SAR), patent document (PD), and institutional documents (ID) from public and private agencies and companies in the green hydrogen production sector. The bibliometric analysis of SAR allows qualify and quantify technological areas, impacts and trends through indicators on the dynamics and evolution of scientific data, and has been used as to analyze recent advances in green technologies (Jabeen *et al*., 2020; Boloy *et al*., 2021; Bortoluzzi; Souza; Furlan, 2021; Khatun *et al*., 2021; Oliveira; Moutinho, 2021; Reza *et al*., 2021; Simões *et al*., 2021; Zolfaghari *et al*., 2021; Arruda *et al*., 2025; Wang, 2025). The study of information contained in PD has been considered a very efficient method to investigate the history and state of the art in a technology area and enable the prospect of technological trends and routes (Pritchard, 1969; Madani; Weber, 2016; Park *et al*., 2018; Sinigaglia *et al*., 2019; Cader-Marciniak; Koneczna; Olczak, 2021; Spreafico; Russo; Spreafico, 2021). The leading ID used were reports, statical yearbooks and technical notes where commercial and public policy information, both for development and regulation.

Information from SAR was carried out by advanced search on the "Web of Science" database, covering all years of publications and restricting the search by topic (TS), including the title, abstract and keywords. The PD chosen database was FAMPAT by Questel, as it is a worldwide collection that coverage patent applications published by more than 100 patent authorities (Questel, 2021a). The field "title", "abstract", "object of invention" and "claims" was selected, with no time restriction for this research.

The search strategies for data on the modes of hydrogen production from renewable energy sources covered both, for articles and reviews, and for patent documents, using the following keywords:

- Product: ["hydrogen" OR "biohydrogen" OR "bio-hydrogen"];
- Hydrogen type: ["green" OR "renewable" OR "bio" OR "blue" OR "sustainab*"];
- Power supply: ["solar" OR "pv" OR "photovoltaic" OR "wind" OR "organic waste" OR "biomass"];
- Production mode: ["electrol*" OR "gasificat*" OR "steam reform" OR "biophotol*" OR "photo-fermentat*" OR "dark fermentant*" OR "biorefiner*"].

3.2 Data analysis

Data were statistically analyzed by

bibliometrics and patentometric, which allows concluding a large volume of data. For SAR bibliometric data analysis, the OpenRefine software (2021) was used, which mixed synonymous words, the plural with the singular and the abbreviations with their names to merge and reduce the repeated words. In addition, the MS Excel (2021) program was used to build graphs with the data collected in the search to justify and better interpret the results.

Then the VOSviewer software (2021) was used, identifying the main lines of research on the topic with the elaboration of network maps. Its distance is linked to its proximity and connection with the other term. Three indicators were used in this program to interpret the results. The co-authorship indicators between organizations and countries made it possible to identify the relationships according to the number of studies they publish together and their interests. The most productive organizations and countries in each cluster are connected and demonstrate their collaboration through the lines on the network maps. Another indicator used was the co-occurrence of keywords that analyze trends on the subject studied and can be extracted from the title, abstract, or author's keywords list (Eck; Waltman, 2014).

For more qualitative analysis, a systematic literature review was performed using the Prisma method (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes) to analyses and summarize the 10 most cited SAR, based on the author, title, publication year, results, researched area, technique, research purpose, gap and contribution, solution and modeling, and results.

The patent analysis was carried out using the Business Software Questel Orbit Intelligence (Questel, 2021b), which allowed dynamic searches with sophisticated crossings and analysis and instant access to the PD content at each stage.

In addition to these meta-analyses, a deeper investigation was performed on the 2021 alive patents, allowing for evaluation on the recent granted and pending patents for prospecting future trends. The results were also contrasted with the ID of specialized agencies, government, and companies, being discussed together with the SAR results.

4 RESULTS AND DISCUSSIONS

The search for the data was carried out in the first half of 2021, with no time restrictions. The results were initially presented by quantitative analysis (4.1) and then by qualitative analysis (4.2) comparing SAR and PD, which present scientific efforts and new technologies on the topic addressed. In this way, it is possible to study the trend and justify it through theoretical bases analyzing over the years the countries of publication, authors and inventors, the classification of subjects, and patent classes (Huang; Notten; Rasters, 2011).

4.1 Quantitative analysis

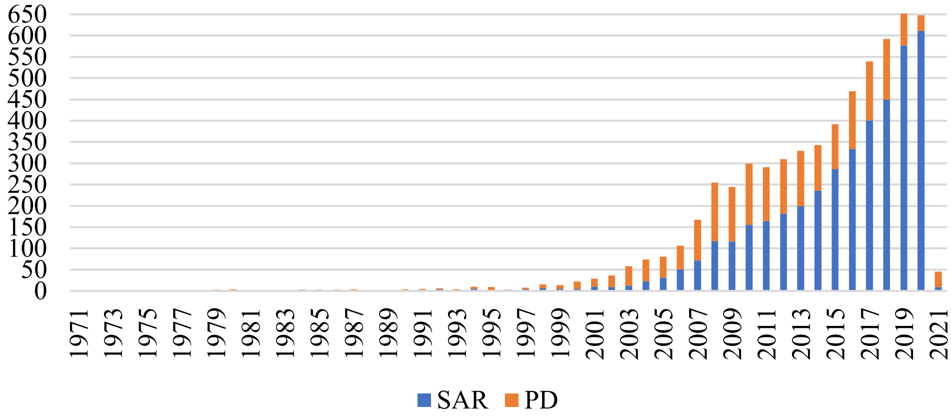
This study found 4080 SAR and 2089 PD in the databases using the keywords determined on hydrogen production with renewable power supply. Regarding the legal status of the PD, it is possible to realize that 66.1% of these documents are alive, with 43.9% granted and 22.2% pending. This indicates that in addition to the current interest in the subject, these inventions have their rights protected and possibly disputed in the global market.

Figure 1 shows the number of publications of SAR and PD accumulated over the years. According to the data, the first patent document applied was in 1949, while the article's publication was only in 1991. The documents present low contributions until the year 2000 when it begins to grow steadily exponentially, especially from 2008, demonstrating the "boom" in the area of renewable energies, in addition to increasing its demand, being three times greater than in 1975, which continues to grow due to political support directly in the investment in hydrogen technologies (International Energy Agency, 2019).

This can also be justified due to the International Partnership for Hydrogen and Fuel Cells in the Economic (IPHE) being established in 2003 by the Department of Energy (DOE) to implement research for development related to hydrogen and fuel cell technologies. This group was initially formed by 16 partners (Germany, Australia, Brazil, Canada, China, European Commission, Russian Federation, United States, France, India, Iceland, Italy, Japan, Norway, Republic of Korea, and the United Kingdom) and a while later New Zealand and South Africa also joined (International Partnership for Hydrogen and Fuel Cells in the Economy, 2021).

The greatest hydrogen production was made through oil products, however, in 2008 the economic crisis occurred, increasing the prices of barrels and thus, the governments started to encourage and promote renewable energies, including hydrogen. In addition to proving to be promising to escape from high oil prices, hydrogen would also come to increase the country's GDP per capita and reduce CO2 emissions (Huang; Notten; Rasters, 2011; International Energy Agency, 2019; Matos, 2024).

Figure 1 - SAR and PD publications over the years



Source: research sources.

Publications continue to grow exponentially and in 2019, the European Union released the European Green Deal, which aims to reduce 55% of emissions by the year 2030 compared to 1990 levels, boost innovations and generate more jobs by the year 2050, also being salvation to get out of the crisis that occurred during the covid-19 pandemic (Belardo, 2021). The proposal on decarbonized hydrogen is to transform it into an innovative energy carrier that can be used as a biofuel in industries and transport, and from 2035 onwards, all new cars will be zero emissions. To ensure that drivers can use this biofuel across Europe, member states will install recharging and refueling points at regular intervals on major highways every 150 kilometers. In addition, several countries are focused on producing zero-emission cars to be able to use hydrogen in fuel cells, such as the USA, Portugal, Germany, the Netherlands, Japan, and other countries. And beside them, since 2020, China has focused on building the fuel cell supply chain and developing hydrogen-powered cars, trucks, and buses, focusing on reducing emissions (Belardo, 2021).

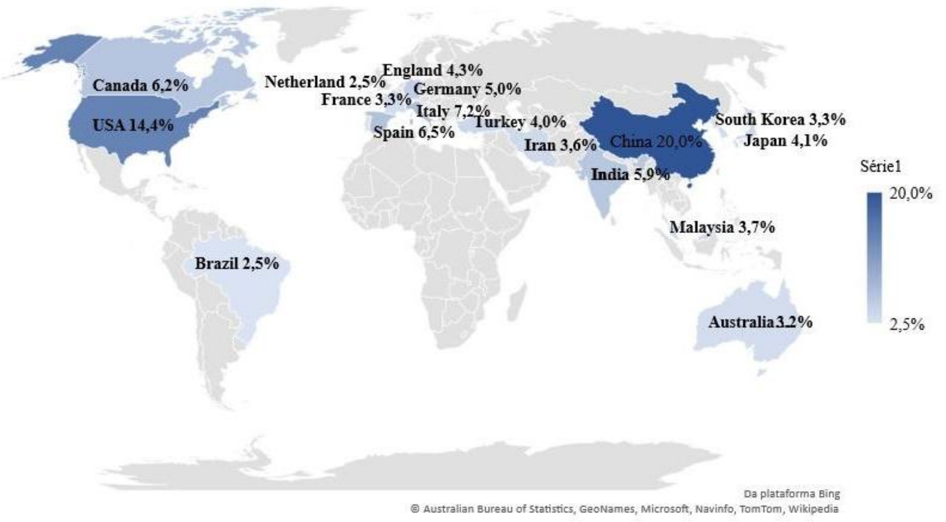
Among the countries that published the most SAR (figure 2), China is in the first place, followed by the USA and Italy with 815, 586 and 295 documents, respectively. It is noteworthy that the amount of work assigned to each country includes international collaborations, thus, adding the amount for each country, it exceeds the amount of 4080 articles.

In addition, the co-authorship between several countries analysis was performed using the VOSviewer software. Clusters are defined as a group of terms that make connections, the links (Rios *et al*., 2022). Thus, each node/circle represents a country. The larger the circle, the greater the number of publications and the closer and thicker the line connecting two countries, the greater the collaboration between them. Figure 3 shows that countries from different clusters collaborate with each other, and the more links a country has, the more it contributes to the international scientific community.

The parameter analyzed in Figure 3 indicates the partnership between countries in the development of articles and it was determined that it should have at least one publication per country. China presented the most significant number of articles published in partnership with countries like the USA, India, Italy, Spain, Canada, Japan, Turkey, Germany, Australia, and England.

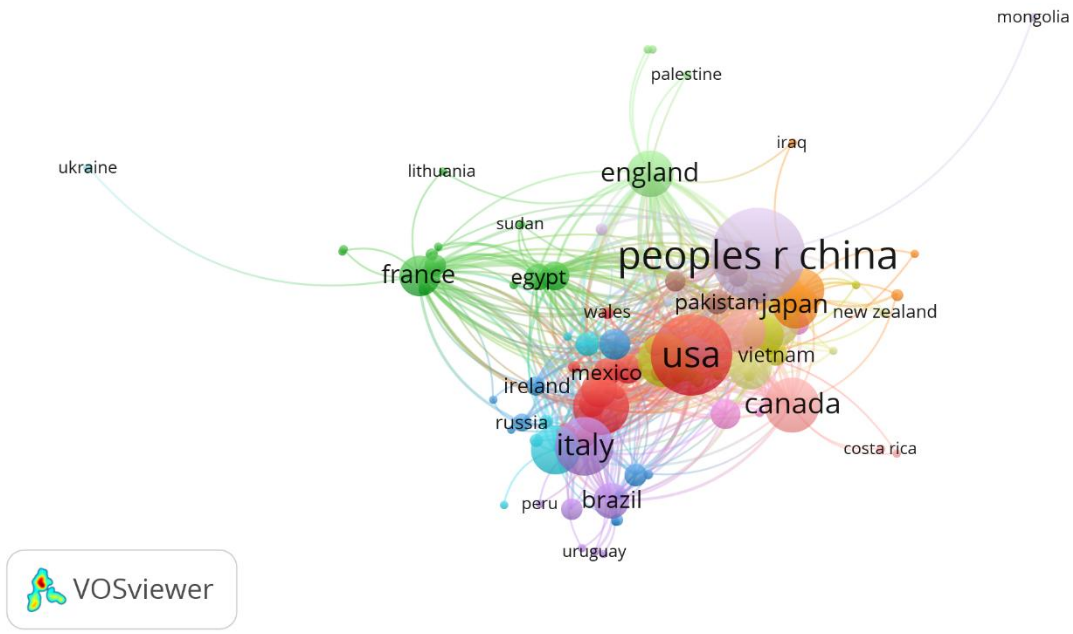
Among the most recent and relevant collaborations are the USA and China collaboration with the article (Kuang *et al*., 2019) that evaluates hydrogen production by water electrolysis, preserving potable freshwater sources, and using solar energy as a sustainable energy source in the process. For that (Kuang *et al.*, 2019) used multilayer anode (NiFe, NiSx and NiFe/ NiSx -Ni), there are superior corrosion resistance of the salty-water-splitting anode.

Figure 2 - Countries with more publications on biohydrogen production



Source: research sources.

Figure 3 - Countries where publications on biohydrogen production are co-authored



Source: research sources.

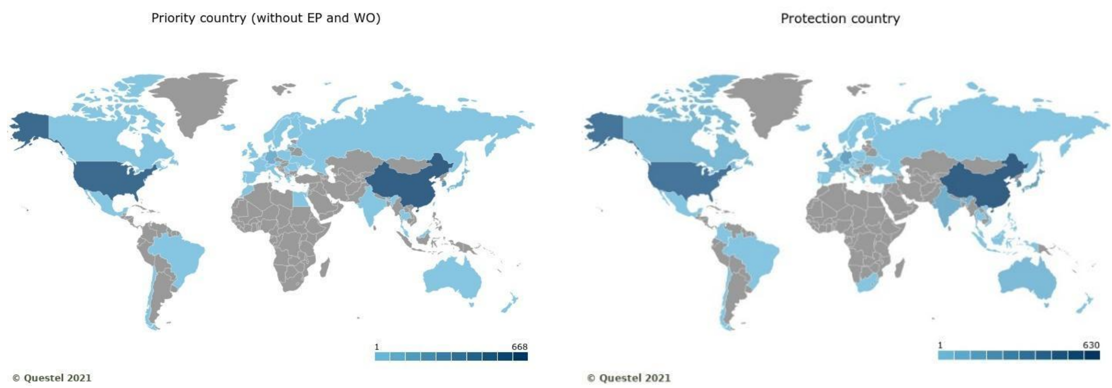
Another article (Cheng *et al*., 2018) is result of the collaboration between the USA, England, and Germany. This work analyzes an unassisted solar water separation system optimization of a photoelectrochemical device based on photovoltaic tandem heterojunctions, where they obtained an efficiency of 19%.

Patent information shows that, as well as scientific production, China and the USA, stand out with 1,015 and 803 PD, respectively published in their patent offices. Soon after comes the requests for protection for several countries through the WIPO – World Intellectual Property Organization (776 PD) and the EPO – European Patent Office (567 PD). Following are the countries: South Korea (499), Japan (469), Canada (249), Germany (237), Australia (220), India (208), Taiwan (179), Brazil (170), and other countries with less than 100 PD in their offices.

These numbers report both resident orders and inventions from other countries that ask for protection in other regions, considering them as a target market. For this reason, the priority requests in each country and the requests for protection of each national office were analyzed separately. Figure 4 shows in gray the countries that do not have patent applications in the area and a variation in the blue color showing the countries with publications.

Figure 4 - Priority countries of (4-A) and Protection countries (4-B) from PD technology on biohydrogen production

(A) (B)



Source: research sources.

As inventors usually first request protection at their own country's patent office, priority countries are generally considered as the origin of the technology presented in the PD, illustrated in Figure 4-a. The largest number of priority PD applications is for China (605), the USA (522), Korea (270), Germany (178), Japan (122) and other countries with less than 100 PD with priority requests.

Figure 4-b illustrates the number of alive (granted and pending) patents protected in the various national offices. Unlike priority requests, this indicator demonstrates applicants' protection strategies. To apply for patents in other countries and maintain them takes cost and time. Countries that have many requests for protection tend to represent a market of interest for commercial exploitation. China stood out with 630 PD, followed by the USA (453), EPO (360), Korea (321), Japan 257, Germany (238), India (171), England (162), Taiwan (155), France (133), Canada (118) and other countries with less than 100 PD.

Overall, China and the USA are the countries that most publish SAR and apply PD with their organizations and currently have construction underway for large-scale hydrogen production (Norouzi, 2021). China's excellent performance at the forefront of developing new technologies to advance the transition from an energy model based on fossil fuels to those of renewable origin is observed in the results presented by this research. Added to this fact, the results show that China is the largest market of interest, both for the huge Chinese domestic market and for companies from other countries that seek to protect their inventions where the manufacturing sites of their competitors are located.

Analyzing the 20 assignees that most applied patents related to hydrogen production, 15 are companies and 5 are research institutes/universities, with four research institutes being Chinese but no companies. However, some institutes are arms of large corporations, such as the Huaneng Clean Energy Research Institute, which is part of the China Huaneng Group Co., Ltd., the big state-owned electricity generation enterprises in China, and since 2014 has been patenting inventions in the renewable hydrogen production field. Other highlights were the Dalian Institute of Chemical Physics, Southeast University Nanjing and Technical Institute of Physics and Chemistry Chinese Academy of Sciences.

In China, coal is the most consumed raw material for energy production, liquid fuels, chemicals, and hydrogen (Zhang *et al*., 2021). However, the country is in transition and implementing renewable strategies using hydrogen, which is transmitted in the country through trucks with compressed gas or as a cryogenic liquid or through pipelines to be used, in large part, for electricity. The technologies in the area are still immature and there is a pattern followed for hydrogen production in the country according to the “Blue Book of Infrastructure Development of China's Hydrogen Energy Industry (2018)” (Norouzi, 2021).

The USA is also great power in developing technologies for renewable hydrogen production and as a target market, even if to a lesser extent than China. Of the 15 companies that most applied patents, 5 are North American, emphasizing the former General Electric (GE), which intensely patented inventions related to hydrogen production between 2003 and 2009. Recently, GE has invested heavily in developing equipment and technologies for renewable hydrogen production (General Eletric, 2019, 2021).

Stands out: the McAlister Technologies, LLC, from Roy McAlister that is a professional engineer, author, entrepreneur, and inventor for around 50 years, been since earliest 2000 researching and patenting on this field since 2010 (McAlister, 2003, 2021; Justia Patents, 2021); the SCIMIST INC, that, for example, developed interesting inventions about mediated electrochemical oxidation process used as a hydrogen fuel generator but didn´t patent an invention since 2003; and the Advanced Green Innovations, founded in 2008 in Arizona, which until 2013 patented inventions related to the production of renewable hydrogen, including in collaboration with the McAlister Technologies (McAlister, 2021).

The 2008 oil crisis and the self-cost of energy at the time prompted the USA to take action in favor of cleaner energy (Reboredo; Ugolini, 2018). Today, the US has become a leader in energy innovation, and hydrogen and fuel cells offer an opportunity to extend that leadership by developing technologies and actively participating in studies such as Hy4Heat, THyGA, and HyDeploy.

Thus, the Roadmap to the United States Hydrogen Economic encourages using this biofuel in automobiles to reduce greenhouse gas emissions, mainly on the West Coast, in California. They already have more than 25,000 vehicles powered in this way, in addition, to plan the price difference between other types of vehicles and fuels by 2025 (UNECE, 2021). In addition, during covid-19, fuel cells and hydrogen gained momentum and performed better in several applications, with biofuel supplied in a gaseous form through pipelines to oil and gas refineries, chemical manufacturers, food processors, and, for smaller areas in bulk liquid form.

Next come European countries, taking into account EPO deposits and the sum of each country separately. Germany certainly stands out for being the fourth country to develop inventions for the production of renewable hydrogen. Among the companies that most filed PD, Merck has 71 patents dealing with renewable hydrogen production. A giant biopharmaceutical company, the german Merck has been operating since 1668 (Merck Group, 2021), strong in innovation and has more than 36,200 PD in general. Although about 80% are dead (expired, lapsed or revoked), the fact that they have 5,558 PD granted and 1,823 pending demonstrates that they are active in the competitive game of innovation. Over the past 20 years, the company has filed an average of around 400 patents per year. The main areas of interest for protecting your inventions are the USA, Japan, China, Taiwan and South Korea. Most patents are focused on the areas of organic fine chemistry and pharmaceuticals, including using hydrogen, as is the case with the product Hydrogen Peroxide 30% (Perhydrol).

Even though it is not its core business, Merck has been carrying out a lot of research and projects to promote renewable energy in recent decades, receiving several sustainability awards, such as the 2012 “Energy Star Sustained Excellence Award” from the US Environmental Protection Agency (EPA) (Merck, 2012). One of the 3 areas of expertise is electronics, developing high-tech products and services for the automotive industry, such as the project entitled "Merck Innovative Concept Car", which presents new solutions for smarter, safer and more sustainable cars (Merck group, 2021). More directly related to renewable hydrogen production are research with fuel cell vehicles, where Merck has been developing a system in which catalyst does not require platinum, inventions inspired by the active centers of blood cells (Merck, 2021).

Another large German company among those that most applied patents was Simens, helping the industrial-scale green hydrogen power in the world, in Germany with the construction of the Wunsiedel Green Hydrogen Plant, the facility which will produce 1,350 tons of hydrogen annually from renewable energy, and in other countries such as Brazil, where a vast $5.4bn green hydrogen facility is developing (Casey, 2021). Many inventions focus on proton exchange membrane (PEM) electrolysis to transform electrical power into hydrogen without releasing carbon dioxide (CO2) (Siemens, 2021).

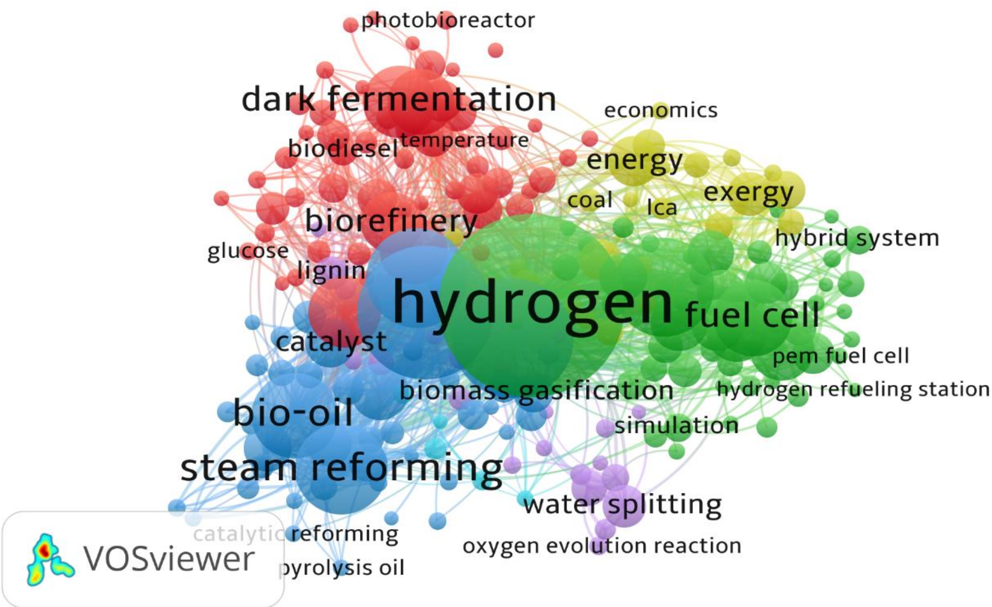
Despite not being among the main developing countries of the analyzed technologies, Honeywell UOP is from the United Kingdom, a company providing innovative hydrogen processing solutions for more than 50 years, being among the 10 companies that most patented inventions the production of renewable hydrogen. Despite historically developing technologies from gray hydrogen, in recent years it has been promoting innovative projects to get more green hydrogen, as “Honeywell H2 Solutions: Ready-now technologies to significantly reduce your carbon footprint” and “UOP PolybedTM PSA Systems: The industry standard for sustainable hydrogen purification and long-term, reliable recovery” (UOP Honeywell, 2021).

South Korea deserves to be highlighted for listing among the top developing countries and even more as a market that needs to be protected. Several companies and research institutes such as Korea Institute of Energy Research have been patenting recent innovations in the field studied. The vital role that public-private partnerships play in the national innovation environment is observed, such as the hydrogen life cycle technologies projects such as the 'Carbon to X Technological Development Project Team,' 'Polyelectrolyte Multilayering (PEM) Electrolysis Core Platform Technology Research Team,' and the 'LOHC-based Hydrogen Discharge System Platform Technology Development Research Team'. These Projects are developed by KIST and LG Chem, South Korean Company that is one of the 10 most applicant of patents searched, with the support of the Ministry of Science and ICT, developing technologies such as CCU (carbon capture & utilization) and hydrogen energy (Chem, 2021).

Like Europe in general, Japan, Canada and Australia have a reasonable number of priority patents and a lot of protection. On the other hand, India, Brazil, and Taiwan show little development in their countries, but great interest as a target market.

On the subject discussed, the co-occurrence of keywords in published SAR was analyzed by applying a restriction of at least 10 occurrences per article, having a total of 209 keywords, as shown in Figure 5.

Figure 5 - Keywords found in SAR on biohydrogen production



Source: research sources.

The words were divided into 5 clusters, classified from the keyword with the most appearing in the publications, presenting the largest node in the group. The green cluster was classified as hydrogen, blue as a steam reform related to other types of production, red as a dark fermentation, yellow as energy, and purple as a water splitting.

Hydrogen is precisely the focus of this work, so the most expected is called a cluster, and the other clusters are connected to it. This cluster has words that refer to how hydrogen is stored and transformed into energy. Storage is a major barrier to the use of hydrogen as an energy source, which has led to studies on the materials and structures used for efficient, cost-effective, and safe storage. Hwang *et al*. (2021) developed a new strategy to achieve a high-capacity hydrogen storage medium through the formation of external and internal carbon fiber pores and the control of surface porosity, achieving an increase of more than 5% in capacity.

Another form of storage is fuel cell systems. Hydrogen has high energy efficiency, surpassing other hydrocarbon fuels, making it have high latency to be used in fuel cells that can be used for domestic, thermal, industrial and transportation energy. There is an international movement to encourage new technologies in this area, aiming to contribute 8-10% in the energy market (Oey *et al*., 2016; Kamaraj; Ramachandran; Aravind, 2020).

The blue cluster is linked to hydrogen production with bio-oils through pyrolysis and steam catalytic reform. There are undesirable and non-combustible compounds in the bio-oil that can act as an acid and interfere with stability, making this bio-oil unsuitable for use as an engine fuel. So, these compounds are being studied a lot because when they are extracted, it's possible to be used to transform hydrogen, as is the case of phenol and acetic acid that have, respectively, 38% and 30% by weight of bio-oil (Nabgan *et al*., 2017).

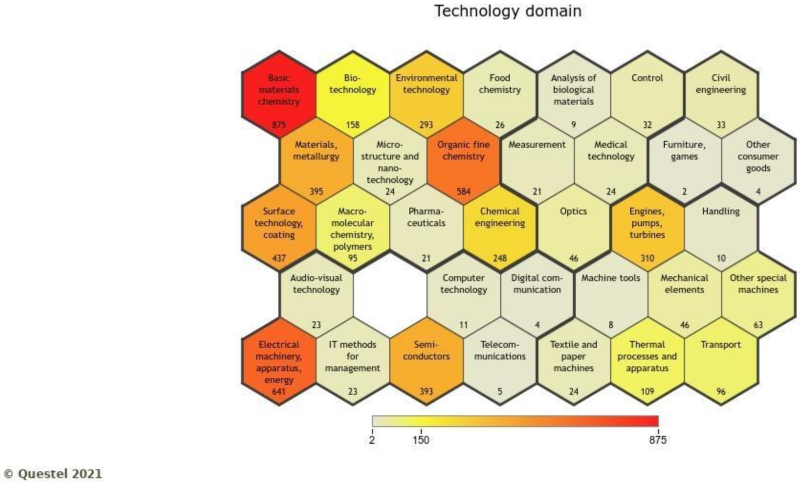
Dark fermentation is very close to the keyword "temperature" because it is an essential factor in the process that can influence biohydrogen production. This parameter can be characterized in four ways: mesophilic, thermophilic, extreme thermophilic, and hypermorphic (Kamaraj; Ramachandran; Aravind, 2020). In addition, it is also very close to the "photobioreactor", because this reactor comes as a solution to integrate production and photo ferment waste from the dark fermentation to generate additional hydrogen in the process (Sarkar; Bhattacharyya, 2012).

The "water splitting" absorbs solar energy and produces hydrogen and oxygen. That is why it is connected and in the same cluster, the purple, the keyword "oxygen evolution reaction". And the yellow cluster is linked to all other clusters because the forms of hydrogen production demand and produce energy, which also involves economic values. However, they are the ones that are less studied. This cluster has the word "exergy" which means that the maximum work can be obtained in the hydrogen production system.

Concerning PD, through the technological domain and the International Patent Classification (IPC), they analyze the trends and innovations associated with hydrogen production. With the IPC, access to technological information is facilitated by organizing all patent documents in groups and subgroups.

Figure 6 shows the direction of these patents for the chemical area, mainly in the section of basic chemical materials and in the area of fine organic chemistry, and for the area of electrical engineering focusing on apparatus, machines, energy, and semiconductors. These domain areas correspond with the focus of the most prominent representative companies, which focus on sustainability, although not in the area.

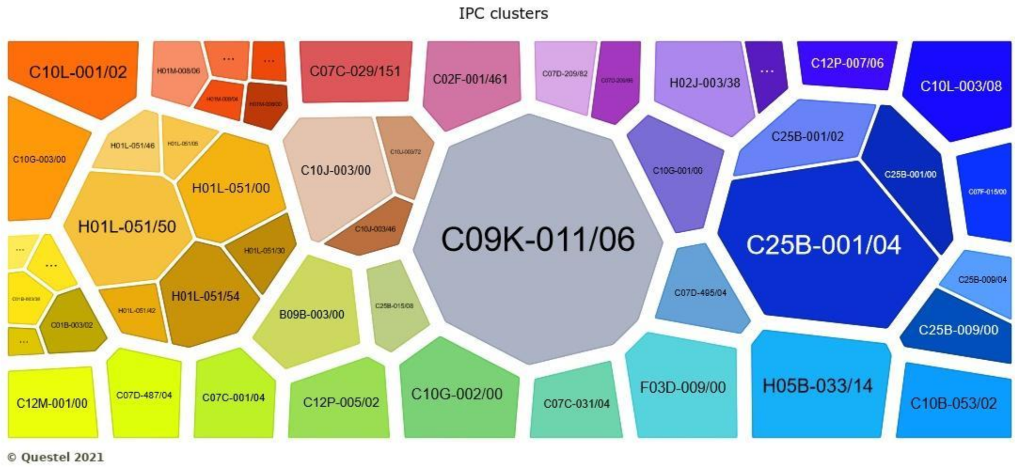
Figure 6 - Technology domain of PD on biohydrogen production



Source: research sources.

Figure 7 shows the clusters with the IPC classifications of the patents found, and another group can represent each document. As already mentioned, and described in Figure 6, hydrogen production focuses on chemistry, represented by section C, and electricity, expressed by section H.

Figure 7 - IPC clusters of biohydrogen production



Source: research sources.

4.2 Qualitative analysis

4.2.1 Scientific Articles and Reviews (SAR)

From the Web of Science database, 4478 articles were identified according to the search strings. After refinement of the results, where only the document in English and original and review articles were evaluated, 4080 articles were reached, which were ordered by citation number, from highest to lowest, being possible to select the ten most cited for of the meta-analysis (Figure 8):

Table A1 in the annex presents the main results found in the 10 most cited articles, has been made and divided into 8 topics: author(s), year of publication, research areas, purpose, production mode, power supply, highlights and key findings.

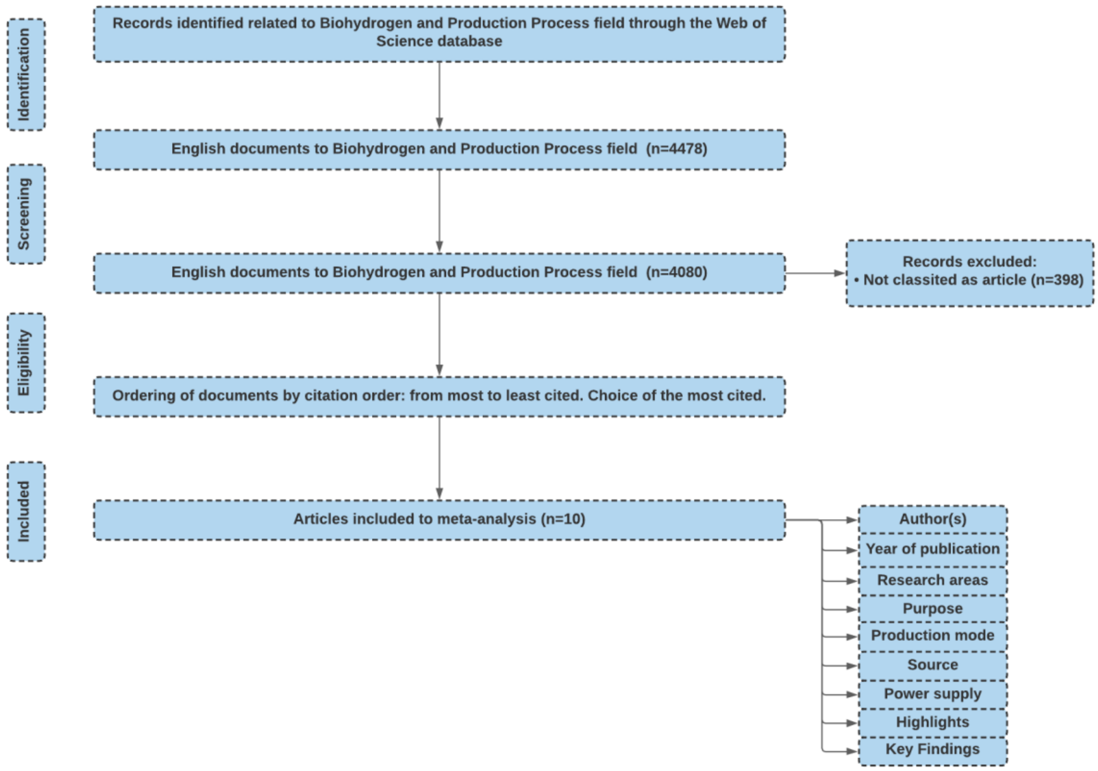
Of the 10 articles evaluated, 3 are experimental articles and 7 are review articles, all 10 of which are interdisciplinary articles. When it comes to the energy source addressed in the works, biomass (n=5), photovoltaic (n=4), solar (n=2) appear, given that some works address up to two different sources. As for the production method, electrolysis (n=7), gasification (n=3), steam reform (n=2) and biorefinery (n=1).

Figure 9 shows the history of citations between the years 2016 and 2020 of the 10 articles considered in the PRISMA method, where 1 indicates the most cited article, 2 the second most cited, and so on.

It is possible to observe the relevance of the works, even in articles that have been published for a long time. The articles in the position of fifth (Cortright; Davda; Dumesic, 2002) and seventh (Alonso; Bond; Dumesic, 2010) most cited, date from 2002, and in recent years have accumulated 34.5% and 34.95%, respectively. On the other hand, the other articles accrued more than 55% of their citations in the period considered. The research area in which all 10 articles fell into was energy fuels, chemistry, and electrochemistry. In addition to these areas, 9 documents were from engineering, 4 from thermodynamics, 3 from materials science, and 1 from physics as well.

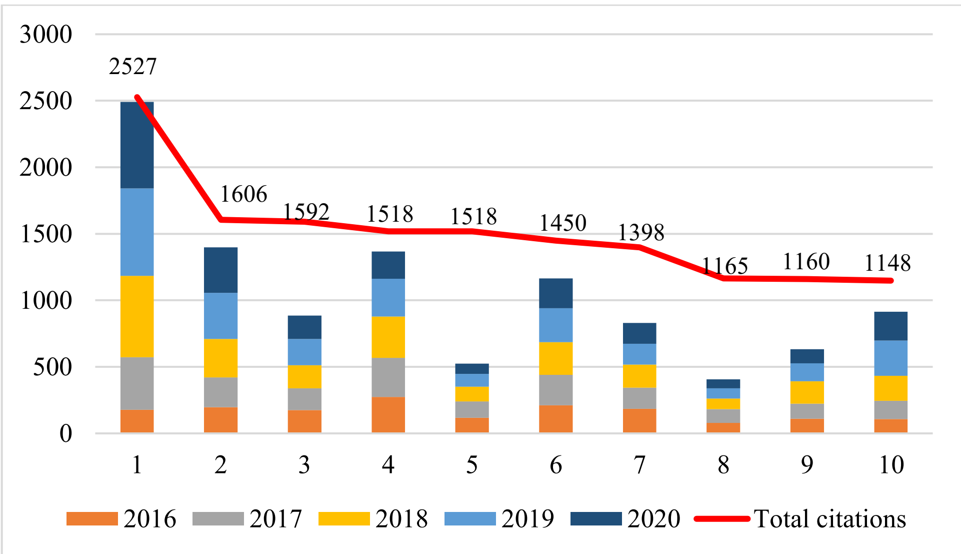
All the analyzed articles emphasize the need to explore renewable energy sources and the search for making them feasible concerning the available energy sources. In this context, hydrogen appears as a promising alternative. Thus, literature reviews were carried out to evaluate resources such as electrocatalysis free of noble metals (Zou; Zhang, 2015), the use of polymer electrolyte membrane (Carmo *et al*., 2013), and the production from different biomasses in the hydrogen production (Cortright; Davda; Dumesic, 2002; Peterson *et al*., 2008; Holladay *et al*., 2009; Panwar; Kaushik; Kothari, 2011). Experimental studies have brought new possibilities in the process of obtaining hydrogen, such as increasing the efficiency of energy conversion with the use of cocatalysts (Yang *et al*., 2013), the reconciliation efficiency and low cost in a water dividing cell with a perovskite solar cell and abundant catalyst bifunctional (Luo *et al.*, 2014) and show that it is possible to produce hydrogen from sugars and alcohols at high temperatures (close to 500 K) using a platinum-based catalyst (Cortright; Davda; Dumesic, 2002).

Figure 8 - Flowchart of the PRISMA method with search results on SAR biohydrogen production



Source: research sources.

Figure 9 - Citation history from 2016 to 2020.



Source: research sources.

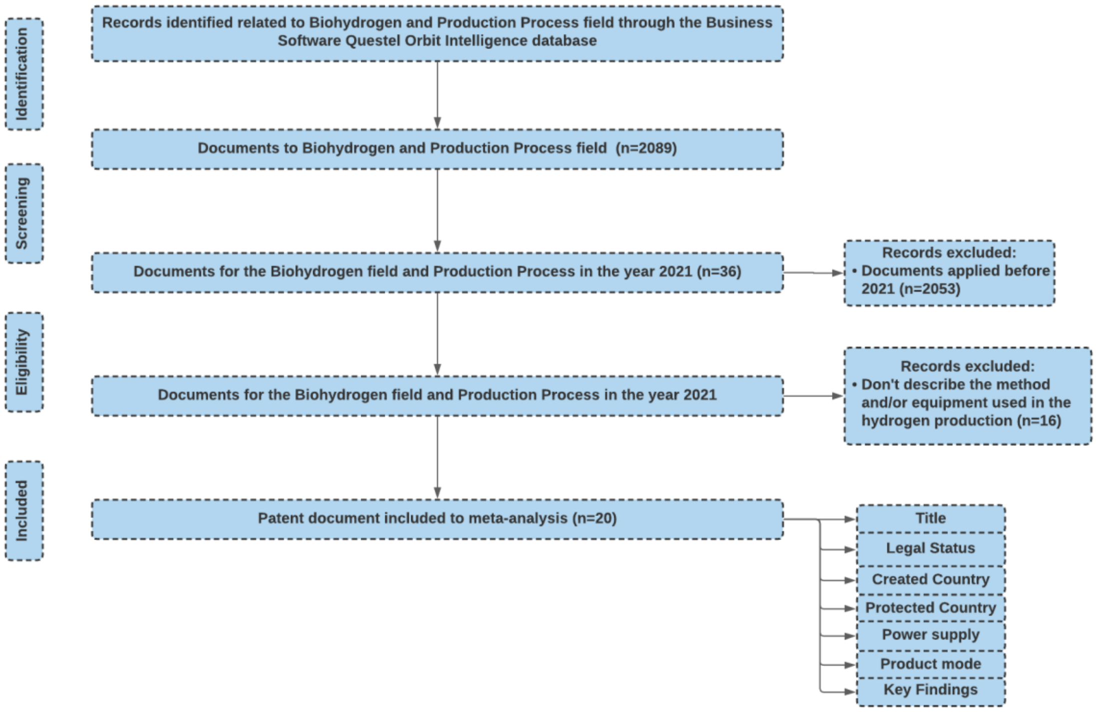
The renewable hydrogen production was, for the most part, from the electrolysis of water and they also point to the use of solar energy, directly (Panwar; Kaushik; Kothari, 2011; Carmo *et al*., 2013; Yang *et al*., 2013) or from photovoltaic cells (Bak *et al*., 2002; Luo *et al*., 2014; Zou; Zhang, 2015) as a source of energy for this process, as well as (Carmo *et al*., 2013) wind energy.

Some studies sought to present the best material used for the electrodes (Bak *et al*., 2002; Yang *et al*., 2013; Luo *et al*., 2014; Zou; Zhang, 2015) or in coating membranes (Carmo *et al*., 2013). Other critical highlights are the mitigation of CO_2 from the biohydrogen production in a closed and decentralized system of photovoltaic energy production (Panwar; Kaushik; Kothari, 2011) and the use of molecules smaller than sugars, which make the process more efficient (Cortright; Davda; Dumesic, 2002).

4.2.2 Patent Documents (PD)

Qualitative analysis of patent documents was performed in the Business Software Questel Orbit Intelligence database, filtering only the alive deposits from 2021 to determine a global trend towards hydrogen production from renewable sources (Figure 10). The 36 PD requests were found, of which only 20 describe the method and/or equipment used in production. The 16 PD discarded were the same orders or did not approach the biohydrogen production, only used to produce other materials.

Figure 10 - Flowchart of the PRISMA method with search results on PD biohydrogen production



Source: research sources.

Table A2 in the annex shows the main topics analyzed in the 20 PD: The title, legal status, the country where it was created and where the technology is protected, the power supply, the production mode, and the key findings of the document.

Of the documents analyzed, 18 are pending requests from China (n=14) India (n=1), and South Korea (n=1), and only 2 are granted and applied by Indian's people with a request for protection in Australia focusing on production for remote areas, such as the country's islands.

All deposits have efficient technologies and equipment for hydrogen production from water electrolysis, mainly using solar and wind energy sources, proving to be a global trend. In addition to using freshwater, seawater can be used in the process, undergoing some pre-treatments before. The use of other energy sources in the electrolysis process was also observed, such as biomass and tidal and wave.

5 CONCLUSION

In general, national states, private companies, and the scientific community show great interest in developing research, technologies, and innovations for renewable hydrogen production. From 2000 onwards, an intense growth in the number of SAR and PD can be seen, with 2008 being the great boom in the sector. External geopolitical and macroeconomic factors such as the price of oil and the pressure to face climate change, and the creation of public policies for regulation and development directly affect the development of these technologies. China and the USA have the greatest power in developing technologies and target markets, with solid public policies to encourage renewable hydrogen production. Chinese technology developers are more closely linked to State Research Institutes and universities than private companies, an inverse profile observed in the USA.

Japan, Canada, Australia and European countries such as Germany and the United Kingdom stand out as developers and even more interesting markets. Among the top developing countries and even more as a market that needs protection, South Korea presents a development profile strongly supported by public-private partnerships. Developing countries such as Brazil, India and Taiwan show little local technological development but awaken interest in protection from other countries. There is a migration of areas of interest both from large industries from other sectors and non-renewable energy industries to renewable hydrogen.

SAR presents energy fuels as the most significant area, it is the use of hydrogen as fuel and fuel cell by electrochemistry to generate electrical or thermal energy, used in the biofuel reform process used in the solid-oxide cell, focusing on the use of hydrogen as a vehicle fuel. PD demonstrates predominance for the chemical area, mainly in the section of basic chemical materials and in the area of fine organic chemistry, and for the area of electrical engineering focusing on apparatus, machines, energy, and semiconductors.

Water electrolysis is the most common way to produce biohydrogen using solar and wind energy as a source. Several countries are focused on developing technologies and investing in research to build equipment that develops the production process, such as electrolytes. Improvements in production costs need to be applied to increase competitiveness in the current market and promote decentralized energy production, taking advantage of the resources of each region.

In this sense point the use of co-catalysts manufactured with non-noble materials and more abundant in nature even as points to the challenges of reconciling the efficiency of photoelectrodes with low cost, using the promising technology of perovskite and solar cells, the challenges of increasing cell life and point oxide materials as the most promising photoelectrodes, as they are inexpensive, resistant to corrosion and present stable performance over time.

REFERENCES

ALONSO, D. M.; BOND, J. Q.; DUMESIC, J. A. Catalytic conversion of biomass to biofuels. **Green Chemistry**, v. 12, n. 9, p. 1493–1513, aug. 2010. DOI: https://doi.org/10.1039/C004654J

ANAND, C. *et al.* Green hydrogen for a sustainable future: A review of production methods, innovations, and applications. **International Journal of Hydrogen Energy**, v. 111, p. 319-341, mar. 2025. DOI: https://doi.org/10.1016/j.ijhydene.2025.02.257. Disponível em: https://www.researchgate.net/publication/389320637_Green_Hydrogen_for_a_Sustainable_Future_A_Review_of_Production_Methods_Innovations_and_Applications. Acesso em: 02/01/2025

ARRUDA, V. C. L. *et al.* LOW-carbon hydrogen production via bioenergetic systems: A bibliometric and systematic review. **Next Research**, v, 2, n. 2, p. 100257-12, mar. 2025. DOI: http://dx.doi.org/10.1016/j.nexres.2025.100257. Disponível em: https://www.researchgate.net/publication/389945197_LOW-CARBON_HYDROGEN_PRODUCTION_VIA_BIOENERGETIC_SYSTEMS_A_BIBLIOMETRIC_AND_SYSTEMATIC_REVIEW. Acesso em: 02/01/2025

BAK, T. *et al.* Photo-electrochemical hydrogen generation from water using solar energy. Materials-related aspects. **International Journal of Hydrogen Energy**, v. 27, n. 10, p. 991–1022, oct. 2002. DOI: https://doi.org/10.1016/S0360-3199(02)00022-8. Disponível em: https://www.researchgate.net/publication/2233222

12_Photo-Electrochemical_Hydrogen_Generation_From_Water_Using_Solar_Energy_Materials-Related_Aspects. Acesso em: 13/01/2025

BAYKARA, S. Z. Hydrogen: A brief overview on its sources, production and environmental impact. **International Journal of Hydrogen Energy**, v. 43, n. 23, p. 10605–10614, mar. 2018. DOI: http://dx.doi.org/10.1016/j.ijhydene.2018.02.022. Disponível em: https://www.researchgate.net/publication/323568359_Hydrogen_A_brief_overview_on_its_sources_production_and_environmental_impact. Acesso em: 14/12/2024

BELARDO, T. **What you need to know about the European Green Deal - and what comes next**. Disponível em: https://www.weforum.org/stories/2021/07/what-you-need-to-know-about-the-european-green-deal-and-what-comes-next/>. Acesso em: 15 out. 2021.

BOLOY, R. A. M. *et al.* Waste-to-Energy Technologies Towards Circular Economy: a Systematic Literature Review and Bibliometric Analysis. **Water, Air, & Soil Pollution**, v. 232, n. 7, p. 306, jul. 2021. DOI: https://link.springer.com/article/10.1007/s11270-021-05224-x. Disponível em: https://www.researchgate.net/publication/353195578_Waste-to-Energy_Technologies_Towards_Circular_Economy_a_Systematic_Literature_Review_and_Bibliometric_Analysis. Acesso em: 14/12/2024

BORTOLUZZI, M.; SOUZA, C. C. de; FURLAN, M. Bibliometric analysis of renewable energy types using key performance indicators and multicriteria decision models. **Renewable and Sustainable Energy Reviews**, v. 143, p. 110958, jun. 2021. DOI: https://doi.org/10.1016/j.rser.2021.110958. Disponível em: https://www.researchgate.net/publication/349961099_Bibliometric_analysis_of_renewable_energy_types_using_key_performance_indicators_and_multicriteria_decision_models. Acesso em: 07/02/2024

CADER-MARCINIAK, J.; KONECZNA, R.; OLCZAK, P. The Impact of Economic, Energy, and Environmental Factors on the Development of the Hydrogen Economy. **Energies**, v. 14, n. 16, p. 4811, aug. 2021. DOI: http://dx.doi.org/10.3390/en14164811. Disponível em: https://www.researchgate.net/publication/353750174_The_Impact_of_Economic_Energy_and_Environmental_Factors_on_the_Development_of_the_Hydrogen_Economy. Acesso em: 07/02/2024

CARMO, M. *et al.* A comprehensive review on PEM water electrolysis. **International Journal of Hydrogen Energy**, v. 38, n. 12, p. 4901–4934, apr. 2013. DOI: http://dx.doi.org/10.1016/j.ijhydene.2013.01.151. Disponível em: https://www.researchgate.net/publication/236902272_A_comprehensive_review_on_PEM_electrolysis. Acesso em: 07/02/2024

CASEY, J. P. **Siemens begins work on 8.75MW green hydrogen plant in Germany**. Disponível em: https://www.power-technology.com/news/siemens-begins-work-on-8-75mw-green-hydrogen-plant-in-germany/. Acesso em: 11 out. 2021.

CHEM, L. G. **LG Chem and KIST Begin Joint Development of Carbon Neutral Breakthrough Technologies**. Disponível em: https://www.lgchem.com/company/information-center/press-release/news-detail-8591?lang=en_GLOBAL. Acesso em: 9 out. 2021.

CHENG, W. H. *et al.* Monolithic Photoelectrochemical Device for Direct Water Splitting with 19% Efficiency. **ACS Energy Letters**, v. 3, n. 8, p. 1795–1800, jun. 2018. DOI: http://dx.doi.org/10.1021/acsenergylett.8b00920. Disponível em: https://www.researchgate.net/publication/325984304_Monolithic_Photoelectrochemical_Device_for_Direct_Water_Splitting_with_19_Efficiency. Acesso em: 07/02/2024

CHI, J.; YU, H. Water electrolysis based on renewable energy for hydrogen production. **Cuihua Xuebao/Chinese Journal of Catalysis**, v. 39, n. 3, p. 390–394, mar. 2018. DOI: http://dx.doi.org/10.1016/S1872-2067(17)62949-8. Disponível em: https://www.researchgate.net/publication/323827706_Water_electrolysis_based_on_renewable_energy_for_hydrogen_production. Acesso em: 17/01/2025

CORTRIGHT, R. D.; DAVDA, R. R.; DUMESIC, J. A. Hydrogen from catalytic reforming of biomass-derived hydrocarbons in liquid water. **Nature**, v.

418, n. 6901, p. 964–967, sep. 2002. DOI: http://dx.doi.org/10.1038/nature01009. Disponível em: https://www.researchgate.net/publication/11188956_Hydrogen_from_catalytic_reforming_of_biomass-derived_hydrocarbons_in_liquid_water. Acesso em: 09/12/2024

DAWOOD, F.; ANDA, M.; SHAFIULLAH, G. M. Hydrogen production for energy: An overview. **International Journal of Hydrogen Energy**, v. 45, n. 7, p. 3847–3869, jan. 2020. DOI: http://dx.doi.org/10.1016/j.ijhydene.2019.12.059. Disponível em: https://www.researchgate.net/publication/338534224_Hydrogen_production_for_energy_An_overview. Acesso em: 17/01/2025

DINCER, I. Green methods for hydrogen production. **International Journal of Hydrogen Energy**, v. 37, n. 2, p. 1954–1971, jan. 2012. DOI: http://dx.doi.org/10.1016/j.ijhydene.2011.03.173. Disponível em: https://www.researchgate.net/publication/251580397_Green_methods_for_hydrogen_production. Acesso em: 09/12/2024

DOU, B. *et al.* Activity of Ni-Cu-Al based catalyst for renewable hydrogen production from steam reforming of glycerol. **Energy Conversion and Management**, v. 78, p. 253–259, feb. 2014. DOI: http://dx.doi.org/10.1016/j.enconman.2013.10.067. Disponível em: https://www.researchgate.net/publication/259120645_Activity_of_Ni-Cu-Al_based_catalyst_for_renewable_hydrogen_production_from_steam_reforming_of_glycerol. Acesso em: 17/01/2025

ECK, N. J. van; WALTMAN, L. **Visualizing Bibliometric Networks**. In: DING, Y.; ROUSSEAU, R.; WOLFRAM, D. (eds) **Measuring Scholarly Impact**. Springer, Cham, 2014. DOI: https://doi.org/10.1007/978-3-319-10377-8_13.

ENERGY TRANSITIONS COMMISSION. **Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Eletrified Economy**. *[S.l.: S.n.],* apr. 2021. Disponível em: https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/. Acesso em: 17/01/2025

GENERAL ELETRIC. **POWER TO GAS: HYDROGEN FOR POWER GENERATION**. *[S.l.: S.n.]*. Feb. 2019. Disponível em: https://www.gevernova.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861-Power-to-Gas-Hydrogen-for-Power-Generation.pdf. Acesso em: 09/12/2024

GENERAL ELETRIC. **The Road to Zero: New York Power Plant Teams with GE On ‘Green Hydrogen’ Demonstration Project**. Disponível em: https://www.ge.com/news/reports/the-road-to-zero-new-york-power-plant-teams-with-ge-on-green-hydrogen-demonstration-project. Acesso em: 10 out. 2021.

GUO, S. *et al.* Enhancement of pH values stability and photo-fermentation biohydrogen production by phosphate buffer. **Bioengineered**, v. 11, n. 1, p. 291–300, jan. 2020. DOI: http://dx.doi.org/10.1080/21655979.2020.1736239. Disponível em: https://www.researchgate.net/publication/339705640_Enhancement_of_pH_values_stability_and_photo-fermentation_biohydrogen_production_by_phosphate_buffer. Acesso em: 09/12/2024

HOLLADAY, J. D. *et al.* An overview of hydrogen production technologies. **Catalysis Today**, v. 139, n. 4, p. 244–260, 2009. DOI: http://dx.doi.org/10.1016/j.cattod.2008.08.039. Disponível em: https://www.researchgate.net/publication/222301887_An_Overview_of_Hydrogen_Production_Technologies. Acesso em: 17/01/2025

HUANG, C.; NOTTEN, A.; RASTERS, N. Nanoscience and technology publications and patents: A review of social science studies and search strategies. **The Journal of Technology Transfer**, v. 36, n. 2, p. 145–172, 2011. DOI: https://doi.org/10.1007/s10961-009-9149-8. Disponível em: https://link.springer.com/article/10.1007/s10961-009-9149-8#Bib1. Acesso em:c09/12/2024

HWANG, S. H. *et al.* The enhanced hydrogen storage capacity of carbon fibers: The effect of hollow porous structure and surface modification. **Nanomaterials**, v. 11, n. 7, p. 1–13, jul. 2021. DOI: http://dx.doi.org/10.3390/nano11071830. Disponível em: https://www.researchgate.net/publication/353253045_The_Enhanced_Hydrogen_Storage_Capacity_of_Carbon_Fibers_The_Effect_of_Hollow_Porous_Structure_and_Surface_Modification. Acesso em: 17/01/2025

INTERNATIONAL ENERGY AGENGY. **The Future of Hydrogen: Seizing today's opportunities.** Proposed Documents for the Japanese Presidency of the G20. Japan, jun. 2019. Disponível em: https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf. Acesso em: 17/01/2025

INTERNATIONAL ENERGY AGENGY. **The Future of Hydrogen -** Seizing today's opportunities. *[S.I.: S.n.]*. IEA (2019), Disponível em: https://www.iea.org/reports/the-future-of-hydrogen. Acesso em: 09/12/2024

INTERNATIONAL PARTNERSHIP FOR HYDROGEN AND FUEL CELLS IN THE ECONOMY. Hydrogen strategies and roadmaps. **Partners**. Disponível em: https://www.iphe.net/partners. Acesso em: 15 out. 2021.

JABEEN, S. *et al.* A comparative systematic literature review and bibliometric analysis on sustainability of renewable energy sources. **International Journal of Energy Economics and Policy**, v. 11, n. 1, p. 270–280, dec. 2020. DOI: http://dx.doi.org/10.32479/ijeep.10759. Disponível em: https://www.researchgate.net/publication/347314187_A_Comparative_Systematic_Literature_Review_and_Bibliometric_Analysis_on_Sustainability_of_Renewable_Energy_Sources. Acesso em: 17/01/2025

JUSTIA PATENTS. **Patents by Inventor Roy E. McAlister**. Disponível em: https://patents.justia.com/inventor/roy-e-mcalister. Acesso em: 11 out. 2021.

KAMARAJ, M.; RAMACHANDRAN, K. K.; ARAVIND, J. Biohydrogen production from waste materials: benefits and challenges. **International Journal of Environmental Science and Technology**, v. 17, n. 1, p. 559–576, nov. 2020. DOI: http://dx.doi.org/10.1007/s13762-019-02577-z. Disponível em: https://www.researchgate.net/publication/337073454_Biohydrogen_production_from_waste_materials_benefits_and_challenges. Acesso em: 28/11/2024

KHATUN, R. *et al.* Bibliometric analysis of research trends on the thermochemical conversion of plastics during 1990–2020. **Journal of Cleaner Production**, v. 317, p. 128373, jul. 2021. DOI: http://dx.doi.org/10.1016/j.jclepro.2021.128373. Disponível em: https://www.researchgate.net/publication/353333918_Bibliometric_analysis_of_research_trends_on_the_thermochemical_conversion_of_plastics_during_1990-2020. Acesso em: 28/11/2024

KUANG, Y. *et al.* Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels. **Proceedings of the National Academy of Sciences of the United States of America**, v. 116, n. 14, p. 6624–6629, mar. 2019. DOI: http://dx.doi.org/10.1073/pnas.1900556116. Disponível em: https://www.researchgate.net/publication/331871593_Solar-driven_highly_sustained_splitting_of_seawater_into_hydrogen_and_oxygen_fuels. Acesso em: 28/11/2024

LEVIN, D. B.; CHAHINE, R. Challenges for renewable hydrogen production from biomass. **International Journal of Hydrogen Energy**, v. 35, n. 10, p. 4962–4969, may 2010. DOI: http://dx.doi.org/10.1016/j.ijhydene.2009.08.067. Disponível em: https://www.researchgate.net/publication/222822771_Challenges_for_renewable_hydrogen_production_from_biomass. Acesso em: 17/01/2025

LI, J. *et al*. Recent Advances and Perspectives on Coupled Water Electrolysis for Energy-Saving Hydrogen Production. **Advanced Science**, v. 12, n. 7, p. 2411964, jan. 2025. DOI: https://doi.org/10.1002/advs.202411964. Disponível em: https://advanced.onlinelibrary.wiley.com/doi/10.1002/advs.202411964. Acesso em: 28/11/2024

ŁUKAJTIS, R. *et al.* Hydrogen production from biomass using dark fermentation. **Renewable and Sustainable Energy Reviews**, v. 91, n. april 2017, p. 665–694, aug. 2018. DOI: http://dx.doi.org/10.1016/j.rser.2018.04.043. Disponível em: https://www.researchgate.net/publication/345638960_Hydrogen_production_from_biomass_using_dark_fermentation. Acesso em: 17/11/2024

LUO, J. *et al.* Water photolysis at 12.3% efficiency via perovskite photovoltaics and Earth-abundant catalysts. **Science**, v. 345, n. 6204, p. 1593–1596, sep. 2014. DOI: http://dx.doi.org/10.1126/science.1258307.

Disponível em: https://www.researchgate.net/publication/266208328_Water_photolysis_at_123_efficiency_via_perovskite_photovoltaics_and_Earth-abundant_catalysts. Acesso em: 28/11/2024

MADANI, F.; WEBER, C. The evolution of patent mining: Applying bibliometrics analysis and keyword network analysis. **World Patent Information**, v. 46, p. 32–48, sep. 2016. DOI: http://dx.doi.org/10.1016/j.wpi.2016.05.008. Disponível em: https://www.researchgate.net/publication/303697648_The_evolution_of_patent_mining_Applying_bibliometrics_analysis_and_keyword_network_analysis. Acesso em: 28/11/2024

MARTINO, M. *et al.* Main hydrogen production processes: An overview. **Catalysts**, v. 11, n. 5, apr. 2021. DOI: http://dx.doi.org/10.3390/catal11050547. Disponível em: https://www.researchgate.net/publication/351093194_Main_Hydrogen_Production_Processes_An_Overview. Acesso em: 28/11/2024

MATOS, T. F. de. Certificados de energia renovável-conceituação através de uma revisão sistemática de literatura. **Revista Eletrônica de Gestão e Tecnologias Ambientais**, v. 12, n. 2, p. 174-187, dez. 2024. DOI: http://dx.doi.org/10.9771/gesta.v0i2.62632. Disponível em: https://www.researchgate.net/publication/387770042_CERTIFICADOS_DE_ENERGIA_RENOVAVEL_-_CONCEITUACAO_ATRAVES_DE_UMA_REVISAO_SISTEMATICA_DE_LITERATURA. Acesso em: 08/01/2025

MCALISTER, R. **The Solar Hydrogen Civilization**: The Future of Energy Is the Future of Our Global Economy. *[S.l.]*: American Hydrogen Association, 2005.

MCALISTER, R. **Metrol Hydrogen Fuel**. Disponível em: https://metrol-hydrogen-fuel.com/message-from-roy-mcalister/. Acesso em: 11 out. 2021.

MERCK. **Merck Receives 2012 ENERGY STAR® Sustained Excellence Award from U.S. Environmental Protection Agency (EPA)**. Disponível em: https://www.merck.com/news/merck-receives-2012-energy-star-sustained-excellence-award-from-u-s-environmental-protection-agency-epa/. Acesso em: 10 out. 2021.

MERCK. **FUEL CELL VEHICLES WITH A HEART INSPIRED BY BLOOD**. Disponível em: https://www.merckgroup.com/en/research/science-space/envisioning-tomorrow/scarcity-of-resources/sustainable-fuel-cells.html. Acesso em: 10 out. 2021.

MERCK GROUP. **Expertise**. Disponível em: https://www.merckgroup.com/br-pt/expertise/automotive.html. Acesso em: 10 out. 2021.

NABGAN, W. *et al.* Renewable hydrogen production from bio-oil derivative via catalytic steam reforming: An overview. **Renewable and Sustainable Energy Reviews**, v. 79, p. 347–357, nov. 2017. DOI: https://doi.org/10.1016/j.rser.2017.05.069.

NOROUZI, N. An overview on the renewable hydrogen generation market. **International Journal of Energy Studies**, v. 6, n. 1, p. 67–94, jul. 2021. Disponível em: https://www.researchgate.net/publication/352953241_An_overview_on_the_renewable_hydrogen_generation_market. Acesso em: 08/01/2025

OEY, M. *et al.* Challenges and opportunities for hydrogen production from microalgae. **Plant Biotechnology Journal**, v. 14, n. 7, p. 1487-1499, jul. 2016. DOI: https://doi.org/10.1111/pbi.12516.

OLIVEIRA, H.; MOUTINHO, V. Renewable Energy, Economic Growth and Economic Development Nexus: A Bibliometric Analysis. **Energies**, v. 14, n. 15, p. 4578, 2021.

PALANIVEL, P. D. *et al.* Harnessing dark fermentation: Mechanisms, metabolic pathways, and nanoparticle innovations for biohydrogen enhancement. **International Journal of Hydrogen Energy**, v. 109, p. 383-396, mar. 2025. DOI: https://doi.org/10.1016/j.ijhydene.2025.02.033. Disponível em: https://www.sciencedirect.com/science/article/abs/pii/S0360319925005993?via%3Dihub. Acesso em: 08/01/2025

PANWAR, N. L.; KAUSHIK, S. C.; KOTHARI, Surendra. Role of renewable energy sources in environmental protection: A review. **Renewable and Sustainable Energy Reviews**, v. 15, n. 3, p.

1513–1524, apr. 2011. Disponível em: https://ideas.repec.org/a/eee/rensus/v15y2011i3p1513-1524.html. Acesso em: 17/01/2025

PARK, Y. N. *et al.* The structure and knowledge flow of building information modeling based on patent citation network analysis. **Automation in Construction**, v. 87, p. 215–224, mar. 2018. DOI: http://dx.doi.org/10.1016/j.autcon.2017.12.023. Disponível em: https://www.researchgate.net/publication/345671726_The_structure_and_knowledge_flow_of_building_information_modeling_based_on_patent_citation_network_analysis. Acesso em: 08/01/2025

PETERSON, A. A. *et al.* Thermochemical biofuel production in hydrothermal media: A review of sub- and supercritical water technologies. **Energy and Environmental Science**, v. 1, n. 1, p. 32–65, jul. 2008. DOI: http://dx.doi.org/10.1039/b810100k. Disponível em: https://www.researchgate.net/publication/248843424_Thermochemical_biofuel_production_in_hydrothermal_media_A_review_of_sub-_and_supercritical_water_technologies. Acesso em: 04/01/2025

PRITCHARD, A. Statistical bibliography or bibliometricas? **Journal of Documentation**, v. 25, n. 4, p. 348–349, jan. 1969. Disponível em: https://www.researchgate.net/publication/236031787_Statistical_Bibliography_or_Bibliometrics. Acesso em: 08/01/2025

QUESTEL. **The Fampat Collection**. Disponível em: https://static.orbit.com/orbit/help/1.9.8/en/index.html#!Documents/thefampatcollection.htm. Acesso em: 3 jun. 2021a.

QUESTEL. **Orbit Intelligence**: business intelligence software. Disponível em: https://www.questel.com/business-intelligence-software/orbit-intelligence/. Acesso em: 2 jun. 2021b.

REBOREDO, J. C.; UGOLINI, A. The impact of energy prices on clean energy stock prices. A multivariate quantile dependence approach. **Energy Economics**, v. 76, p. 136–152, oct. 2018. DOI: https://doi.org/10.1016/j.eneco.2018.10.012.

REZA, M. S. *et al.* Energy storage integration towards achieving grid decarbonization: A bibliometric analysis and future directions. **Journal of Energy Storage**, v. 41, p. 102855, jun. 2021. DOI: http://dx.doi.org/10.1016/j.est.2021.102855. Disponível em: https://www.researchgate.net/publication/352737275_Energy_storage_integration_towards_achieving_grid_decarbonization_A_bibliometric_analysis_and_future_directions. Acesso em: 17/01/2025

RIOS, E. M. *et al.* Dual-fuel compression-ignition engines fuelled with biofuels. A bibliometric review. **Environment Systems and Decisions,** v. 42, p.8-25, mar. 2022. DOI: https://link.springer.com/article/10.1007/s10669-021-09826-y. Disponível em: https://www.researchgate.net/publication/353669372_Dual-fuel_compression-ignition_engines_fuelled_with_biofuels_A_bibliometric_review. Acesso em: 08/01/2025

SARKAR, J.; BHATTACHARYYA, S. Application of graphene and graphene-based materials in clean energy-related devices Minghui. **Archives of Thermodynamics**, v. 33, n. 4, p. 23–40, 2012.

SIEMENS. **Hydrogen from Electrolysis: The Most Versatile Fuel**. Disponível em: https://new.siemens.com/au/en/company/topic-areas/sustainable-energy/the-power-of-hydrogen.html. Acesso em: 11 out. 2021.

SIMÕES, A. J. A. *et al.* A Bibliometric Study on the Application of Advanced Oxidation Processes for Produced Water Treatment. **Water, Air, and Soil Pollution**, v. 232, n. 7, p. 297, 2021. DOI: https://link.springer.com/article/10.1007/s11270-021-05247-4. Disponível em: https://www.researchgate.net/publication/353037132_A_Bibliometric_Study_on_the_Application_of_Advanced_Oxidation_Processes_for_Produced_Water_Treatment. Acesso em: 08/01/2025

SINIGAGLIA, T. *et al.* Use of patents as a tool to map the technological development involving the hydrogen economy. **World Patent Information**, v. 56, p. 1–8, sep. 2019. DOI: http://dx.doi.org/10.1016/j.wpi.2018.09.002. Disponível em: https://www.researchgate.net/publication/327847407_Use_of_patents_as_a_tool_to_map_the_technological_development_involving_the_hydrogen_economy. Acesso em: 17/01/2025

SPREAFICO, C.; RUSSO, D.; SPREAFICO, M. Investigating the evolution of pyrolysis technologies through bibliometric analysis of patents and papers. **Journal of Analytical and**

Applied Pyrolysis, v. 159, n. 3, p. 105021, jan. 2021. DOI: http://dx.doi.org/10.1016/j.jaap.2021.105021. Disponível em: https://www.researchgate.net/publication/348687002_Investigating_the_evolution_of_pyrolysis_technologies_through_bibliometric_analysis_of_patents_and_papers. Acesso em: 08/01/2025

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE. **Draft Roadmap for production and use of hydrogen in Ukraine in road transport**. *[S.l.: S.n.]*. 2021. Disponível em: **https://unece.org/documents/2021/03/reports/draft-roadmap-production-and-use-hydrogen-ukraine**, 2021.Acesso em: 27/12/2024

UOP HONEYWELL. **Hydrogen**: Targeted hydrogen recovery with high purity and reliability. Disponível em: https://uop.honeywell.com/en/industry-solutions/refining/hydrogen. Acesso em: 9 out. 2021.

URSÚA, A.; GANDÍA, L. M.; SANCHIS, P. Hydrogen production from water electrolysis: Current status and future trends. **Proceedings of the IEEE**, v. 100, n. 2, p. 410–426, feb. 2012. DOI: http://dx.doi.org/10.1109/JPROC.2011.2156750. Disponível em: https://www.researchgate.net/publication/220473374_Hydrogen_Production_From_Water_Electrolysis_Current_Status_and_Future_Trends. Acesso em: 22/12/2024

VIJAYA KRISHNA, S. *et al*. Biohydrogen production from brewery effluent in a batch and continuous reactor with anaerobic mixed microbial consortia. **Biofuels**, v. 8, n. 6, p. 701–707, aug. 2016. Doi: https://doi.org/10.1080/17597269.2016.1206409.

XIE, D. *et al*. A comparative review of biohydrogen and biomethane production from biowaste through photo-fermentation. **Green Chemistry**, v. 27, n. 5, 2024. DOI: http://dx.doi.org/10.1039/D4GC06079B. Disponível em: https://www.researchgate.net/publication/387389362_A_comparative_review_on_biohydrogen_and_biomethane_production_from_biowaste_through_photo-fermentation. Acesso em: 17/01/2025

WANG, Z. *et al.* Hydrogen production from biomass: A review combined with bibliometric analysis. **International Journal of Hydrogen Energy**, v. 117, p. 271-291, apr. 2025. DOI: http://dx.doi.org/10.1016/j.ijhydene.2025.03.158. Disponível em: https://www.researchgate.net/publication/390384606_Hydrogen_production_from_biomass_A_review_combined_with_bibliometric_analysis. Acesso em: 15/12/2024

WU, Y. N. *et al.* Best mode for photo-fermentation hydrogen production: The semi-continuous operation. **International Journal of Hydrogen Energy**, v. 41, n. 36, p. 16048–16054, sep. 2016. DOI: https://doi.org/10.1016/j.ijhydene.2016.05.182.

YANG, J. *et al.* Roles of Cocatalysts in Photocatalysis and Photoelectrocatalysis. **Accounts of Chemical Research**, v. 46, n. 8, p. 1900–1909, mar. 2013. DOI: http://dx.doi.org/10.1021/ar300227e. Disponível em: https://www.researchgate.net/publication/236082408_Roles_of_Cocatalysts_in_Photocatalysis_and_Photoelectrocatalysis. Acesso em: 22/12/2024

ZHANG, Y. *et al.* Hydrogen production through biomass gasification in supercritical water: A review from exergy aspect. **International Journal of Hydrogen Energy**, v. 44, n. 30, p. 15727–15736, feb. 2019. DOI: http://dx.doi.org/10.1016/j.ijhydene.2019.01.151. Disponível em: https://www.researchgate.net/publication/331091160_Hydrogen_production_through_biomass_gasification_in_supercritical_water_A_review_from_exergy_aspect. Acesso em: 22/12/2024

ZHANG, B. *et al.* Progress and prospects of hydrogen production: Opportunities and challenges. **Journal of Electronic Science and Technology**, v. 19, n. 2, jun. 2021. DOI: https://doi.org/10.1016/j.jnlest.2021.100080.

ZOLFAGHARI, Z. *et al.* Direct air capture from demonstration to commercialization stage: A bibliometric analysis. **International Journal of Energy Research**, v. 46, n. 1, p. 383-396, aug. 2021. Disponível em: https://www.researchgate.net/publication/354177493_Direct_air_capture_from_demonstration_to_commercialization_stage_A_bibliometric_analysis. Acesso em: 17/01/2025

ZOU, X.; ZHANG, Y. Noble metal-free hydrogen evolution catalysts for water splitting. **Chemical Society Reviews**, v. 44, n. 15, p. 5148–5180, apr. 2015. DOI: http://dx.doi.org/10.1039/c4cs00448e.

ANNEX:

Table A 1. PRISMA method with search results on SAR biohydrogen production

Author(s)	Year of publication	Research areas	Purpose	Production mode	Power Supply	Highlights	Key Findings
Zouc, X and Zhang, Y.	2013	Energy fuels, Chemistry, Electrochemistry Materials Science	Through the review to analyze the recent studies on the sustainable use of electrocatalysts free of noble metals and their catalytic properties for the hydrogen evolution reaction (HE).	Electrolysis	Photovoltaic	Kinds of Electrocatalysts: Metals - sulfides, selenides, carbides, nitrides, phosphides, and heteroatom-doped nano carbon	There are several important kinds of heterogeneous non-precious metal electrocatalysts, emphasizing synthetic methods, the strategies of performance improvement, and the structure/composition-catalytic activity relationship. Finally, some examples that use these electrocatalysts like cocatalysts to promote direct solar conversion to hydrogen in photochemical and photoelectrochemical
Carmo, M; Fritz, D. L; Mergel, J; Stolten, D.	2013	Energy fuels, Chemistry, Engineering, Electrochemistry Thermodynamics Materials Science	The state-of-the-art for the PEM electrolysis technology. (Review)	Electrolysis	Solar and Wind	PEM - polymer electrolyte membrane	Art study on the results already achieved in different membranes, catalysts, ionomers, current collectors, separator plates (...) and the challenges to direct further studies with PEM electrolysis as an economically viable hydrogen production, in addition to the possibility of coupling of solar and wind energy.
J.D. Holladay, J. Hu, D.L. King, Y. Wang	2008	Energy fuels, Chemistry, Engineering, Electrochemistry	Review the technologies related to hydrogen production from both fossil and	Electrolysis Steam Reform Gasification	Biomass	Organic Wastes (municipal, agricultural, wood, etc)	Focus on decentralized hydrogen production from different fossil and renewable biomass resources, including reform (steam, partial oxidation, auto thermals, plasma

			renewable biomass resources.				and aqueous phase) and pyrolysis, and through water by electrolysis and other methods, also analyzing storage media and purification.
Luo, J; Im, J. H;. Mayer, M. T; Schreier, M; Nazeeruddin, M. K; Park,N. G; Tilley, S. D; Fan, H. J; Grätzel, M.	2014	Energy fuels, Chemistry, Engineering, Electrochemistry Thermodynamics Physics	Reconciling efficiency and low cost in a water dividing cell with a perovskite solar cell and abundant bifunctional catalyst on Earth.	Electrolysis	Photovoltaic	Perovskite solar cell	Hydrogen production through photochemical water division or by conducted electrolysis (photovoltaic). The challenges of reconciling the efficiency of photoelectrodes and low cost, using the promising technology of perovskite solar cells and the challenges of increasing the cell's life.
R. D. Cortright, R. R. Davda, J. A. Dumesic	2002	Energy fuels, Chemistry, Engineering, Electrochemistry Thermodynamics	To show that it is possible to produce hydrogen from sugars and alcohols at high temperatures (close to 500 K) in a single-reactor aqueous phase reform process using a platinum-based catalyst.	Steam Reform	Biomass Organic Waste	Sugars and alcohols	The use of molecules smaller than sugars is more efficient in producing hydrogen, with ethylene glycol and methanol being almost completely converted into hydrogen and carbon dioxide. Thus, the aqueous catalytic phase presents itself as a viable alternative in the generation of hydrogen-rich fuel gas from carbohydrates extracted from renewable biomass and biomass waste streams.
Yang, J.; Wang D.; Han H.; Li, C.	2012	Energy fuels, Chemistry, Engineering, Electrochemistry	Increase energy conversion efficiency with the use of cocatalysts	Electrolysis	Solar	Cocatalisadores Photoelectrocatalytic (PEC)	Due to the low overall efficiency of energy conversion, given the three steps for the water division reaction, dual approach cocatalysts have a general strategy for the development of efficient photocatalytic systems.

Alonso, D. M; Jesse Q. Bond, J. Q; James A. Dumesic, J. A	2010	Energy fuels, Chemistry, Engineering, Electrochemistry	Critical review for an overview of catalytic strategies for the production of biofuels from aqueous carbohydrate solutions, which are isolated through pre-treatment and hydrolysis of biomass.	Biorefinery	Biomass	Lignocellulose biomass	Coupling strategies that consume hydrogen with those that produce hydrogen in a second-generation fuel biorefinery, using lignocellulose biomass in the production of fuels, chemicals, hydrogen and any heat and energy in the process.
Bak, T; Nowotny, J; Rekas, M; Sorrell, C. C	2002	Energy fuels, Chemistry, Engineering, Electrochemistry Thermodynamics Materials Science	Review focused on the materials of high-efficiency photoelectrochemical cells (PEC's)	Electrolysis	Photovoltaic	Photoelectrochemical cells (PECs) based on TiO_2	Oxide materials are the most promising photoelectrodes, as they are inexpensive, resistant to corrosion and stable performance over time.
Peterson, A. A; Vogel, Lachance, R. P; Fröling, M.; Antal, M. J M. Jr.; Tester J. W.	2008	Energy fuels, Chemistry, Engineering, Electrochemistry,	Review of sub and supercritical water technologies for the thermochemical production of biofuels in various hydrothermal media.	Gaseification	Biomass	Sub- and supercritical water	The development of processes for the gasification of biomass in supercritical water, and the research carried out by the five largest research groups in the world on the subject.
Panwara, N.L.; Kaushikb, S.C.; Kotharia, S.	2011	Energy fuels, Chemistry, Engineering, Electrochemistry,	Review of CO2 mitigation can be carried out utilizing a solar cooker, water heater, dryer, biofuel, improved stoves and hydrogen.	Gaseification Electrolysis	Biomass Photovoltaic	CO_2 mitigation	A solar plant (autonomous photovoltaic energy), can be integrated into a sustainable closed system in the production of O2, H2 and fuel cells. In addition, the application of a biomass gasifier in a small-scale industry is an alternative for decentralized and renewable energy production.

Table A 2. PRISMA method with search results on PD biohydrogen production

Title	Legal Status	Created country	Protected country	Power supply	Product mode	Key finding
Clean hydrogen and renewable energy hydrogen joint production system	Pending	China	CN	Solar and wind	Electrolysis	The patent discloses a system for the joint production of hydrogen from renewable sources (solar and wind) through the electrolysis of water with storage devices.
Large-scale low-cost hydrogen production system and method by electrolysis	Pending	China	CN	-	Electrolysis	The patent document proposes a large-scale hydrogen production system from the electrolysis of water at low costs. The energy generated from this fuel is stored in a station and connected to the electricity grid.
Wind-solar-hydrogen storage complementary uninterrupted power supply system	Pending	China	CN	Solar and wind	Electrolysis	The invention discloses an uninterrupted power supply system with solar, wind and hydrogen energy storage battery with an intelligent control. In the system, solar and wind energy is used to charge the battery and the surplus enters the hydrogen production system through the electrolysis of pure water.
Hybrid renewable energy source coupling hydrogen production method and system	Pending	China	CN	Solar, wind or biomass	Electrolysis	The document describes the method and equipment required for the production of hydrogen by electrolysis with coupling of hybrid renewable sources (biomass, solar and wind) under the condition of minimum total cost of system operation and the condition of minimum electrolysis energy fluctuation.
System for offshore oil field steam thermal power exploitation by using wind power and photovoltaic	Pending	China	CN	Solar and wind	Electrolysis	The invention provides an energy storage system in an offshore oilfield, where it exploits solar and wind energy, to be fed into the thick oil or ultra-thick oil recovery system. In addition, the site has a storage of pure water to produce hydrogen by electrolysis through these sources and supply the low amount of it.
Renewable energy hydrogen production system and control method thereof	Pending	China	CN	Solar and wind	Electrolysis	The invention refers to a system for the production of hydrogen from electrolysis with an on/off control method. The project has the main production with a renewable

						source (solar and wind), assisting with a controller, and with an electrical source, and a general hydrogen storage, however, it can be seen that the cost of producing hydrogen from renewable energy is reduced and engineering feasibility is improved compared to electrical power.
System for generating hydrogen by utilizing abandoned wind and abandoned light	Pending	China	CN	Solar and wind	Electrolysis	The invention document describes the form of production and storage of liquid hydrogen with the aluminium electrolytic process, also obtaining metal in liquid form, using solar and wind energy.
Renewable energy consumption and power grid peak regulation and frequency modulation oriented composite energy storage system and method	Pending	China	CN	-	Electrolysis	The patent demonstrates a composite energy storage method connected to an electrolytic hydrogen production station that is used as a fuel in a fuel cell for renewable energy production.
Novel mobile power supply system	Pending	China	CN	Solar and wind	Electrolysis	The invention document aims to provide a reliable and stable conversion of renewable energy. The mobile energy supply project has systems for photovoltaic and wind energy generation, for electrolytic water, for hydrogen purification, for hydrogen storage, for the fuel battery and for a controller.
Modeling and planning method for multi-source heterogeneous fully-renewable energy source thermoelectric storage coupling system	Pending	China	CN	Solar and wind	Electrolysis	The invention refers to a method of modelling and planning a thermoelectric storage coupling system with different renewable sources, including solar, wind and hydrogen. In the project, the hydrogen itself is produced electrolytically.
System and method for generation of oxygen and hydrogen using wind energy	Pending	India	IN	Wind	Electrolysis	The patent document refers to a system with several modules for generating hydrogen and oxygen. The system in question comprises a vertical wind turbine to convert wind energy into mechanical energy and then into electrical energy which is used as a source in the electrolysis module and thus produces and stores hydrogen and oxygen in the other module in a liquid form.
A hybrid solar pv, wind, mhd and pem fuel cell-based energy conversion system	Granted	India	AU	Solar and wind	Electrolysis	The invention demonstrates an off-grid electric power system with four types of renewable energy sources (solar, wind, MHD AC generator, and a PEM fuel cell) to meet the demand of remote areas. In addition, the PEM fuel cell acts

						as an electrolyser and an energy storage battery, thus converting water into hydrogen to charge its own battery using the other energies of the system as a source.
Hydrogen production power supply with double staggered BUCK topology and control method thereof	Pending	China	CN	Solar and wind	Electrolysis	The document describes the production of hydrogen through electrolysis based on the topology of the double-interleaved BUCK series with an in-system control using a large-scale wind or photovoltaic energy source. The aim of the invention is to overcome previous problems and provide a feed device for the production of fuel with a high level of pressure resistance and high power.
A fresh water system capable of producing hydrogen gas	Pending	South Korea	KR	Solar	Electrolysis	The document describes a system for the production of gaseous hydrogen through the electrolysis of water with solar energy as a source. In the process, the seawater undergoes a chlor-alkali desalination treatment, then comes into contact with the electrodes and produces the gas.
Renewable electric energy storage system	Pending	China	CN	-	Electrolysis	The invention describes a renewable electric energy storage system with a water electrolysis unit for hydrogen production, a methanol synthesis unit, and an energy generation unit. Renewable energy generation uses the co-product of methanol production, oxygen, and hydrogen produced in the plant.
Oxyhydrogen supply device for plateau area	Pending	China	CN	Solar and wind	Electrolysis	The patent relates to an oxyhydrogen (HHO) supply device for power generation in plateau areas. In the process, hydrogen is produced through renewable sources and by the electrolysis method.
Island and reef integrated energy support system	Pending	China	CN	Solar, wind, tidal or wave	Electrolysis	The patent discloses a system that covers multiple renewable energy sources that are stored in a generator on an island. In addition, there is a device for the production of hydrogen from sea water through electrolysis using stored renewable sources and having it as fuel to be used as another source of energy.
Sustainable electricity generation system system	Pending	India	IN	Solar	Electrolysis	The invention describes a sustainable electric power generation system installed in public lavatories for its own

						use, having a hybrid power system. Using a photovoltaic power supply, the urine solution from the site is electrolytically dissociated to produce hydrogen, which is preserved in a cylinder of compressed gas.
Hybrid energy generation system	Granted	India	AU	Solar	Electrolysis	The patent document describes a hybrid power generation device from a photovoltaic array, a biomass unit, and a hydrogen tank that can be monitored and controlled through a remote server. The hydrogen tank is connected to the biomass tank and configured to receive the unit's gases, in addition to electrolytically transforming the water into hydrogen gas to generate energy in a fuel cell.
Development of brown gas based thermo jet type engine	Pending	India	IN	Solar	Electrolysis	The invention concerns a vehicle that produces brown gas, known as oxy-hydrogen (HHO), using a simplified jet engine that works according to the Lenoir cycle. The production of gas takes place from the hydrolysis of water using a low-voltage solar battery, which generates an impulse to move the car from the exhaust gases, which consist of 90% of water vapor.