




Article

# Fuel-Cell Electric Vehicles: Plotting a Scientific and Technological Knowledge Map

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Received: 23 February 2020; Accepted: 13 March 2020; Published: 17 March 2020



**Abstract:** The fuel-cell electric vehicle (FCEV) has been defined as a promising way to avoid road transport greenhouse emissions, but nowadays, they are not commercially available. However, few studies have attempted to monitor the global scientific research and technological profile of FCEVs. For this reason, scientific research and technological development in the field of FCEV from 1999 to 2019 have been researched using bibliometric and patent data analysis, including network analysis. Based on reports, the current status indicates that FCEV research topics have reached maturity. In addition, the analysis reveals other important findings: (1) The USA is the most productive in science and patent jurisdiction; (2) both Chinese universities and their authors are the most productive in science; however, technological development is led by Japanese car manufacturers; (3) in scientific research, collaboration is located within the tri-polar world (North America–Europe–Asia-Pacific); nonetheless, technological development is isolated to collaborations between companies of the same automotive group; (4) science is currently directing its efforts towards hydrogen production and storage, energy management systems related to battery and hydrogen energy, Life Cycle Assessment, and greenhouse gas (GHG) emissions. The technological development focuses on technologies related to electrically propelled vehicles; (5) the International Journal of Hydrogen Energy and SAE Technical Papers are the two most important sources of knowledge diffusion. This study concludes by outlining the knowledge map and directions for further research.

**Keywords:** fuel cell electric vehicle; bibliometric analysis; patent analysis

## 1. Introduction

The increase in energy use and related emissions was generated by a higher demand for heat from the residential and commercial sectors and road transport demand; consequently, road transport greenhouse gas (GHG) emissions increased for the second subsequent year, continuing the upward trend in emissions that started in 2014 [1]. The electrification of mobility is an essential element in a wider strategy for achieving reduced greenhouse gas emissions [2]. During the previous century, the automotive industry transformed society, bringing new technologies to the market that enhanced their internal combustion engine vehicles, such as global electric vehicles, which are known as one of the most hopeful alternatives for lowering transport-sector carbon dioxide emissions [3,4]. An Electric Vehicle (EV) is a road vehicle that includes electric propulsion. With this definition in mind, EVs may include battery electric vehicles (BEV), hybrid electric vehicles (HEV), and fuel-cell electric vehicles (FCEV) [5]. As sustainable products, FCEVs bring hope for solving several mobility-related problems, as they have no local emissions [6]. One of the most promising ways to achieve an ideal zero-emissions replacement is to use cleanly produced electricity from non-fossil fuels, such as hydrogen, using

fuel-cell technology [7]. Although FCEVs are promising ways to avoid emissions, both technologies are far from being profitable for car manufacturers [6]. In addition, the European Commission [8] set a target for 40% of new cars and vans to be zero- or low-emission vehicles by 2030. Furthermore, in the European Strategic Energy Technology Plan, hydrogen and fuel-cell technologies are identified as the key technologies for achieving GHG reduction targets by 2050 [9,10], and in the European Community Research Program, electromobility is a priority. Here, electric vehicle policy focuses mainly on technology optimization and market development, setting future challenges concerning battery and supercapacitor durability, and charging infrastructure, among others [11]. In turn, the collaborative research and development (R&D) technological projects in Europe are funded by the European Commission [12], and one of the main priorities for transport research and innovation in Horizon 2020 (H2020) is making transport more sustainable [13]; for this reason, the European Commission is promoting clean transport, both for electric vehicles by investing in electromobility initiatives and for FCEVs or hydrogen FCEVs, enabling their commercial development by 2020 [11]. In addition, Edwards et al. [14] performed a roadmap review of deployment status and targets for fuel-cell applications, such as fuel-cell vehicles, and the annual sales forecast was between 0.4–1.87 million during 2020–2025. In order to help all actors involved in clean transport, it is useful to understand how scientific research is evolving and whether it is having an impact on its technological development.

Bibliometric techniques open the door to a fuller understanding of the scientific research carried out on FCEVs, differing from a conventional literature review: The bibliometric method supplies an innovative, objective perspective through reliable, quantitative processes, and has been broadly used in scientific research as an analytical tool to provide assistance to scholars with a general comprehension of typical research topics [15]. According to Garousi [16], bibliometric analysis is a well-established method used to measure publications in a scientific research area, and assessing trends and the value of research is becoming increasingly important [17,18]. According to different authors, bibliometrics is approached in various ways and is defined as a research method, or research technique, that allows scientific literature representing extensive global data sets and reliable data to be analyzed and quantitatively measured [19–21]. We can take this a little further and introduce the term “scientometrics”, defined by Nowak [19]: “Scientometrics focuses on the processes occurring in science” [21]. Scientometrics is the quantitative study of research transfer, and its analysis makes it possible to capture and map scientific knowledge [21–23]. Hence, its main objective is to aid the analysis of emerging trends in the knowledge domain [24]; in addition, knowledge mapping and visualization are meaningful fields of scientometrics [25].

In the main databases, such as Web of Science and Scopus, there is no bibliometric analysis of the “FCEV” research field. However, other bibliometric analyses have been carried out in research fields related to fuel-cell technology. Kang et al. [26] define a diffusion model based on bibliometric analysis applied to fuel-cell technologies. Cindrella et al. [27] present a bibliometric analysis about the field of fuel cells in general from 1992 to 2011, offering a comprehensive overview of trending publications, journals, and countries, and identifying research hotspots through keywords. A similar overview was conducted by Yonoff et al. [28], identifying research trends in Proton Exchange Membrane Fuel Cells (PEMFCs). Related to energy and fuel research in China, Chen et al. [29] conducted a bibliometric analysis and, as a result, hydrogen and fuel cells are among the energy research priorities. Bibliometric studies on energy materials related to hydrogen are also relevant, such as the analysis of sodium borohydride (NaBH<sub>4</sub>) done by Santos and Sequeira [30], as well as on a lithium mineral developed by Agusdinata et al. [31]. Considering that FCEVs are a particular field of EV application, Egbue and Long [32] and Ramirez et al. [33] carried out bibliometric analyses in order to detect the most relevant research points. In turn, Zhao et al. [34] depict a bibliometric analysis for EV charging system reliability to analyze the emerging trends of this active research point, such as in EV batteries.

Patents provide an exclusively detailed source of information of inventive activity [35] and increase the use and commercialization of technologies through market transactions [36], promoting the diffusion of knowledge and innovation. According to Griliches [37], patents are one of the most

influential proxies for assessing the performance of industry research and development (R&D). For these reasons, the patent is an important tool for investigating a technological development from an economic perspective [38]. According to Borgstedt et al. [6], in the automotive industry, patents are the most common way to protect intellectual property, so it can be used as innovative output. Patent data analysis allows us to ascertain the technological state of the studied technology, defining who, when, where, and what is being developed by mining relevant data from patent documents in terms of technology development [39]. In addition, in this case, in the main databases, such as Web of Science and Scopus, there is no patent data analysis of “FCEV” research articles; nevertheless, other research papers related to patents in fuel-cell technologies have been developed. Related to biohydrogen, Leu et al. [38] carried out a patent data and citation analysis. With regard to fuel cells, Chang et al. [40] studied the coactivity between science and technology by analyzing patent–paper pairs. Related to technology forecasting, Chen et al. [41] defined a model for a patent strategy for fuel-cell technologies using the S-curve method.

In demonstrating the evolution of the scientific–technological research of the FCEV domain, this paper offers a comprehensive assessment of the FCEV research practices which were published in the Scopus database from 1999–2019, in order to identify the key actors in the generation and transmission of knowledge related to FCEVs. As far as technological development is concerned, this paper presents the technological trends of industrial developments, mainly led in this case by the automotive industry, in order to establish, among others, who leads the research and development. All this is done in order to draw the FCEV technology knowledge map, to discuss it with the results of other scientific–technological research studies, and, therefore, to be able to predict the future paths of research trends and foreseeable scenarios.

## 2. Materials and Methods

The research process, adapted from Bildosola et al. [42] with some changes, is based on three steps that are intended to define the scientific research activity profile and the technological profile of FCEVs. These steps are developed to answer the questions related to who, where, and what is being or has been researched or developed related to scientific literature and patents. Figure 1 shows the research approach, revealing that each step has its input and output, creating a flow of information that allows the set objectives to be achieved. In each step, the specific technique used is identified. The stages are developed consecutively, until the scientific and technological profiles are determined. However, the objective of this research process is to be able to cover any type of emerging technology or application.

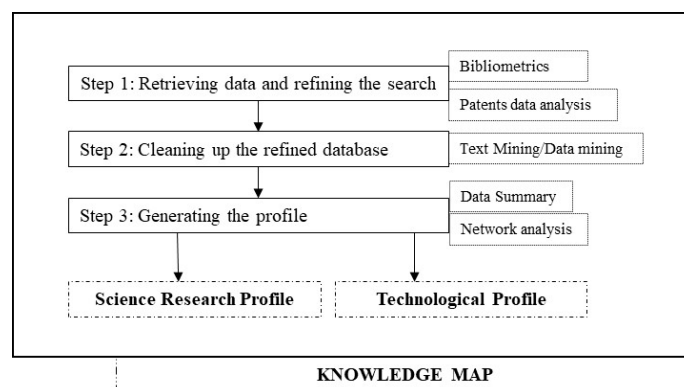


Figure 1. Research process step by step.

Profile generation is carried out through the first three steps, and the main tasks to be carried out are explained below.

Step 1. Retrieving data and refining the search. The first assignment is to generate two specific databases concerning scientific publications and patents related to the emerging technology analyzed.

Regarding the selection of the scientific database, different studies show that better results are obtained [43,44] by using all of the databases (Scopus, Web of Science (WoS), and Google Scholar (GS)). Nevertheless, a very high percentage of WoS and Scopus citations are normally found in GS; those that are not, called unique citations, present a lower scientific impact than WoS and Scopus citations [45]. Furthermore, the two databases complement each other [43]; however, in this case, Scopus returns more citations than WoS. For this reason, in the case of FCEVs, the specific databases were generated from Scopus as the scientific database and Lens as the patent database. Scopus is one of the largest abstract and citation databases of peer-reviewed literature (75 million documents indexed) [46], and it was selected to provide scientific publications. Because blooming technologies meet different approaches, the definition of the search query is very important. In bibliometric search strategies, the balance between recall and precision is very important [47]. However, information scientists usually detect an inverse association between recall and precision [48]. Therefore, the query was built using “fuel-cell vehicle/car/automobile” as author keywords, obtaining a highly precise query. In addition, to achieve greater recall, the search for the same terms based on the index terms is added to the query (see Table 1). Index terms are derived from thesauri that Elsevier owns and are added to improve search recall [46]. The data collection time span was established between 1999 and 2019. In addition, according to Hawkins [49], gatekeeping publications, such as Abstracting and Indexing (A&I) publications, are the main way to identify advances of a technology. Therefore, the query is in line with the document type: Journal Article and Conference Proceeding. The main query used in the Scopus database retrieved a total of 2514 articles and conference papers for the defined time span. The patent analysis was carried out using Lens, a complete open-source global patent database and research platform containing the world’s most comprehensive full-text patent collection. The search for patents relating to FCEVs was carried out on the basis of Cooperative Patent Classification (CPC), also explained as the patent’s field of technological application. Specifically, the search is directed by the classification Y02T90/34—fuel-cell-powered electric vehicles—which makes the results of localized patents far more accurate. The Y CPC was created in order to give a technological application coverage to new technologies that are not included in the International Patent Classification (IPC); Y: General tagging of new technological developments. Y02T90: Technologies for climate-change mitigation or adaptation related to transportation—enabling technologies with a potential or indirect contribution to GHG emission mitigation. In addition, the search was limited to the patent priority year (or the year in which the patent was invented) in the period from 1999 to 2019.

**Table 1.** Search query for fuel-cell electric vehicles adapted to the Scopus database.

Query
AUTHKEY("fuel cell*" W/2 vehicle*) OR AUTHKEY("fuel cell*" W/2 car) OR AUTHKEY("fuel cell*" W/2 cars) OR AUTHKEY ("fuel cell*" W/2 automobile*) OR INDEXTERMS ("fuel cell*" W/2 vehicle*) OR INDEXTERMS ("fuel cell*" W/2 car) OR INDEXTERMS("fuel cell*" W/2 cars) OR INDEXTERMS ("fuel cell*" W/2 automobile*) AND (LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "ar"))

Source: Own work.

Step 2: Cleaning up the refined database. This second task includes the use of text mining tools. The scientific database and the patent database were imported into the Vantage Point (VP) software [50]. VP works with search results from text databases. VP’s capabilities can be broad after importing raw data from scientific databases. VP includes powerful data cleaning tools based on a thesaurus or fuzzy matching techniques. Furthermore, VP integrates powerful techniques for analyzed data, such as natural language programming, a co-occurrence matrix, Principal Component Analysis (PCA), Social Network Analysis (SNA), clusters, and other capabilities for visualizing data. Scientific publications obtained from the previous step were integrated into the database, and in specific fields, such as authors, affiliations, journals, and authors’ keywords, a fuzzy matching was applied in order to group

the variations of a word (plurals, acronyms, and similar expressions, among others) that convey the same meaning.

Step 3: Generating the profile. The profile is divided into two parts: The scientific research profile and the technological profile. The scientific profile is based on the literature profile and research community profile, and these describe the research activity in terms of publication trends, academic performance, research topics, and sources of knowledge. The technological profile deals with issues related to patent trends, the main countries of jurisdiction, inventors and applicants, and the main technological fields. To facilitate the analysis of scientific–technological trends, an analysis of networks was carried out, visualizing the collaborative networks between countries, co-authorship networks, keyword co-occurrences, and collaboration networks of applicants and inventors. For this, starting from the matrices of co-occurrences, created both statically and dynamically in the VP software (Search Technology Inc. Atlanta, USA), the networks were generated and visualized through the Gephi software [51].

### 3. Results

#### 3.1. Scientific Research Profile in FCEVs

##### 3.1.1. General Trends of Publications and Citations

The evolution of publications and citations in the last 20 years is represented in Figure 2 (on a logarithmic basis). Both of them increased sharply, indicating growing academic interest in FCEVs. Whereas in 1999, there were only 13 scientific articles, this number grew to 171 in 2018, an increase of 1215%. Between the years 2005 and 2006, the number of publications jumped markedly and then stabilized with a constant production, 2009 being the most productive year with 203 publications. However, the number of citations per year rapidly increased from 2005, and was over twenty-two times higher in 2018 (5081) than in 2005 (227). Hence, the scientific research community is paying more attention to topics related to cleaner transport. In addition, Figure 2 shows the results of a less precise search of the two terms, displayed independently (query: Fuel cell\* and query: Vehicle\*/car or cars/automobile\*), resulting in a very high number of publications, with a similar growth and continuous increase of both searches.

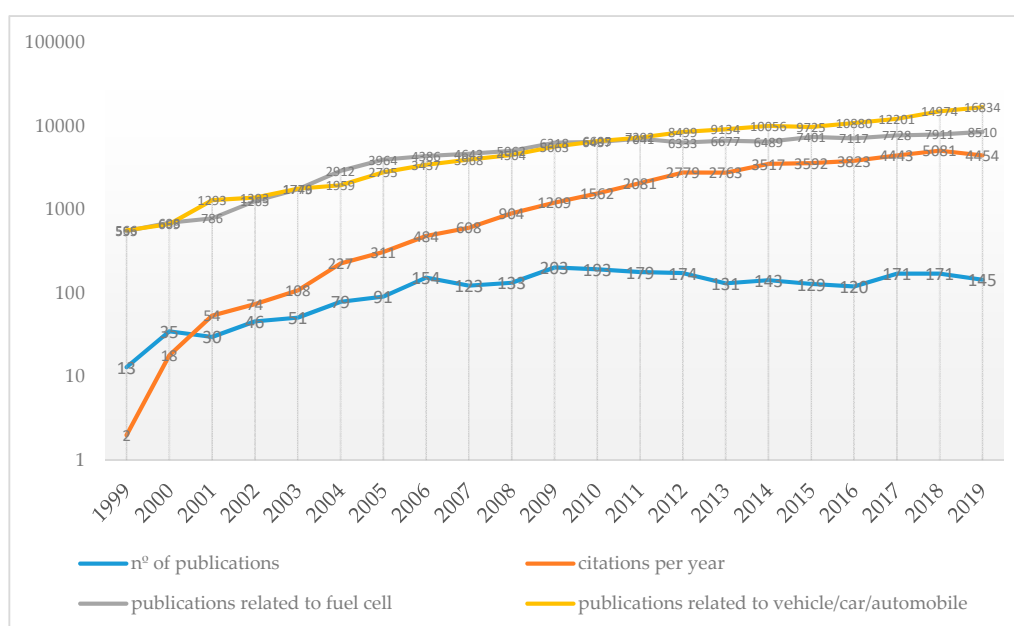
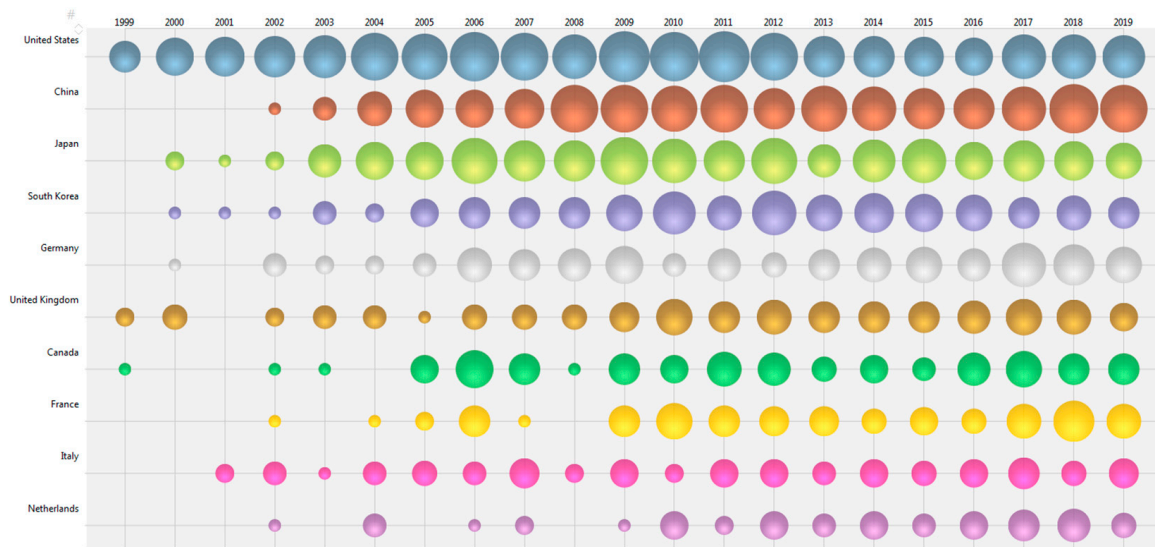


Figure 2. General trends of publications and citations from 1999 to 2019.



### 3.1.2. Academic Performance: Countries, Organizations, and Authors

In total, authors from 61 countries published papers on FCEVs. The affiliations of authors are a good indicator of the specific patterns of research concentration and excellence followed by these countries and organizations. The most advantageous countries in terms of publishing about FCEVs (see Figure 3) are not geographically concentrated, but are rather located in the tri-polar world (North America, Asia-Pacific, and Europe). The two principal countries with the highest number of publications are the USA (618) and China (451). Almost half of the publications are from USA, China and Japan (364).



**Figure 3.** Evolution of the number of articles by country according to publication year, from 1999 to 2019.

In addition, the USA, UK, and Canada stand out as pioneers in scientific research (with regards to the 1999 start date), and they also grew progressively over time. Production in China, despite being the country with the second-most publications, began to be relevant in 2002–2003.

In order to identify collaboration activities between different countries, an effective method is a network analysis. Using Gephi for network analysis, the main countries (countries that have at least three collaborative publications) with international collaborations were identified and plotted (see Figure 4). The size of the node represents the number of connections; consequently, a country with a larger node, such as the USA, is more active in academic collaborations in the field of FCEVs. The width of the connecting line represents the cooperative frequency. Academic collaborations between China, Germany, Japan, and the USA are the most frequent. In the main cluster led by the USA, both European and North American countries, as well as Asian-Pacific countries, are collaborating. The identified collaborations between countries follow the same pattern of collaboration convergence clubs as those related to applied science, as defined by Barrios et al. [52]. In addition, international collaborations are located in a tri-polar world (Europe, North America, and Asia-Pacific); the science powerhouses are countries placed in the central positions of the networks, surrounded by emerging scientific countries. Possible reasons for collaborations may include English language skills, post-colonial links, science skill proximity, economic proximity, and international students, among others [53].

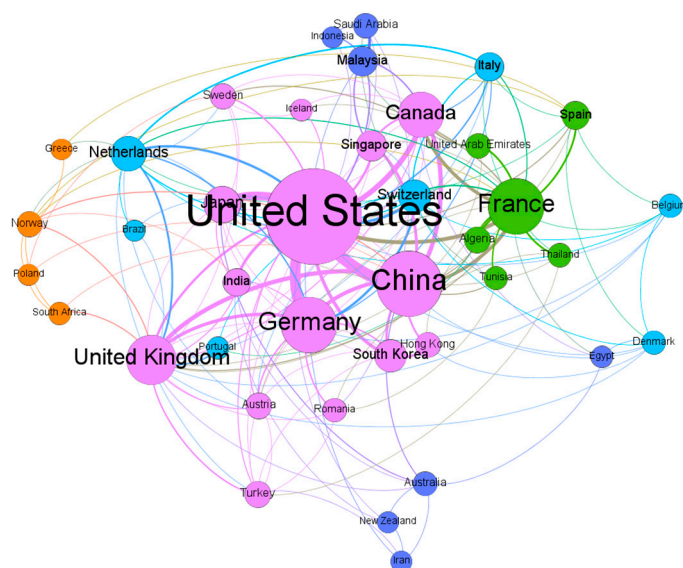


Figure 4. Academic collaborations among the main countries.

According to organizations, Table 2 describes the 10 most active organizations, including the number of publications, their affiliated countries, and their average citations per publication. The most productive organization by far is Tongji University with 134 publications. However, the average citations per publication for the Tsinghua University (ranked #2) is four times greater, and for General Motors (ranked #9), it is seven times greater than for Tongji University. Therefore, this organization (Tongji Univ.) needs to improve the quality of its publications to ensure that its publications become sources of knowledge for other scientific publications. In general, Chinese organizations have fewer average citations per publication, and their publications are concentrated within a few organizations. With the exception of Tongji University, the National Renewable Energy Laboratory, and the US Department of Energy, the publications from the most active organizations do impact academic research. Highlighting the presence of non-academic organizations among the top 10 organizations (General Motors, Ford Motors, and Toyota Motors), the research results have an important impact on the science-driven domain.

Table 2. The most active organizations.

Organization	Publications	Country	Average Citations Per Publication
Tongji University	134	China	3.98
Tsinghua University	76	China	16.72
Toyota Motor Corporation	56	Japan	23.34
University of California, Davis	50	USA	15.00
Argonne National Laboratory	44	USA	17.95
National Renewable Energy Laboratory	44	USA	5.48
Seoul National University	43	South Korea	22.42
Ford Motor Company	41	USA	11.02
General Motors	35	USA	28.91
US Department of Energy	35	USA	9.09

The analysis of the most productive authors (see Table 3) reveals Minggao Ouyang (Tsinghua University, China), Joeri Van Mierlo (Vrije Universiteit, Brussel), and Jianqiu Li (Tsinghua, China) as the three researchers publishing the most in the field. All of the top authors have at least fifteen publications; however, if we evaluate their citation average per publication, important differences between authors appear. For instance, the sixth author, Zuo, S. with 16 publications, has a low average number of citations per publication (2.19), meaning that their academic work has little influence on other scientific research. In general, the top 10 most productive authors have a high average number of

citations per publication, highlighting the authors from Tsinghua University, whose research work has an important influence on other scientific developments.

**Table 3.** Top 10 most productive authors.

Authors	Institution	Country	Counts	Average Citations per Publication	Subject Area <sup>a</sup>
Ouyang, Minggao	Tsinghua University	China	25	33,20	Energy and Engineering
Van Mierlo, Joeri	Vrije Universiteit Brussel	Belgium	23	25,91	Energy and Engineering
Li, Jianqiu	Tsinghua University	China	21	36,90	Energy and Engineering
Xu, Liangfei	Tsinghua University	China	18	42,28	Energy and Engineering
Ravey, Alexandre	Université de Technologie Belfort-Montbéliard	France	16	15,44	Energy and Engineering
Zuo, Shuguang	Tongji University	China	16	2,19	Engineering
Cha, Sukwon	Seoul National University	South Korea	15	17,60	Engineering
Djerdir, Abdesslem	Université Bourgogne Franche-Comté	France	15	6,67	Energy and Engineering
Rathore, Akshay Kumar	Concordia University	Canada	15	26,93	Engineering
Wipke, Keith B.	National Renewable Energy Laboratory	USA	15	8,53	Engineering

<sup>a</sup> Subject areas are summarized from the selected publications in the established dataset (Scopus), taking into account the most frequent subject areas.

A co-authorship network was generated and plotted by using Gephi, as shown in Figure 5, identifying a collaboration network of the top authors (authors with over three publications as co-authorships). The layout of the networks was developed using Force Atlas 2. Each node represents each author, while each link represents the pattern of collaboration. Among the top 10 authors, only the authors affiliated with Tsinghua University (Minggao Ouyang, Jianqiu Li, and Liangfei Xu) have a strong co-authorship between them; the rest of the authors have less intense relationships with other authors who are not in the top 10. The main academic groups can be identified, highlighting that there is no collaboration between them. Five research groups can be identified, whose main authors work in the research field (subject area) of energy and engineering related to FCEVs. Therefore, as far as the research field is concerned, they present few differences, but their locations do: Each group is from a different country or continent (USA, Japan, and Belgium), except for research group 1, in which the authors located in the tri-polar world (France, Canada, USA, China, and South Korea) collaborate, and research group 4, in which authors from China and South Korea collaborate.

### 3.1.3. Sources and Subject Area Classification

Sources with more documents published about FCEVs were identified. The search was limited to journals and conference proceedings, with 60% of the publications published in journals and 40% as conference proceedings. The most productive journal is closely related to hydrogen; however, most of the top journals are related to the automobile industry, electrochemical science, and energy applications. The most notable of the 10 most productive sources was the International Battery, Hybrid, and Fuel-Cell Electric Vehicle Symposium (EVS) organized by the World Electric Vehicle Association (WEVA). The 2514 publications were published in 721 different sources; therefore, the works are not centered around a few journals, but more than 20% were published in two sources. Specially, the International Journal of Hydrogen Energy (271 articles, 10.7%), SAE Technical Papers (257 articles, 10.15%), and Journal of



Power Sources (104 articles, 4.1%) are the top journals (see Figure 6). Moreover, the top journals are indexed in the Clarivate Analytics Journal Citation Report with upper quartile rankings.

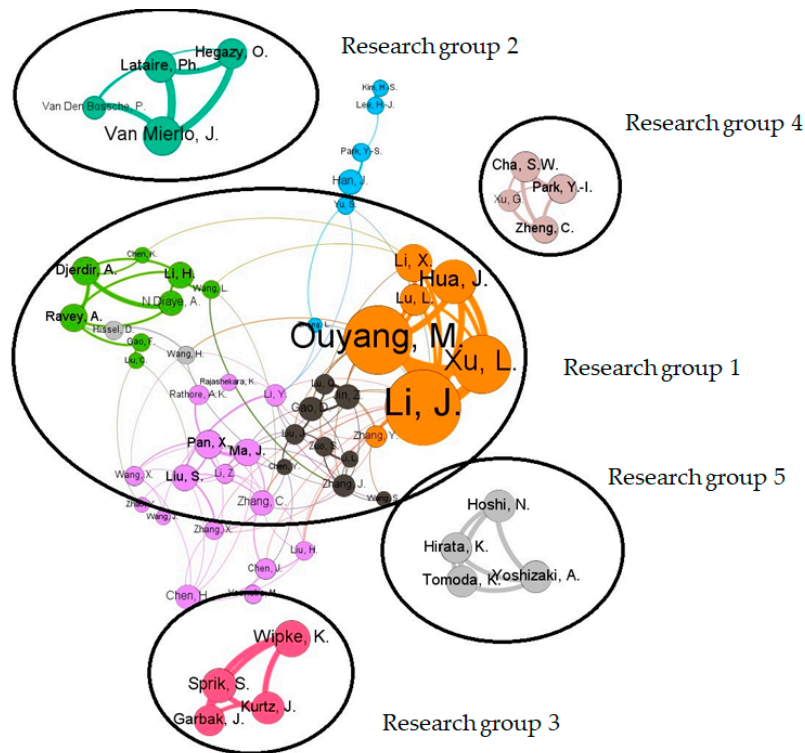


Figure 5. Co-authorship network.

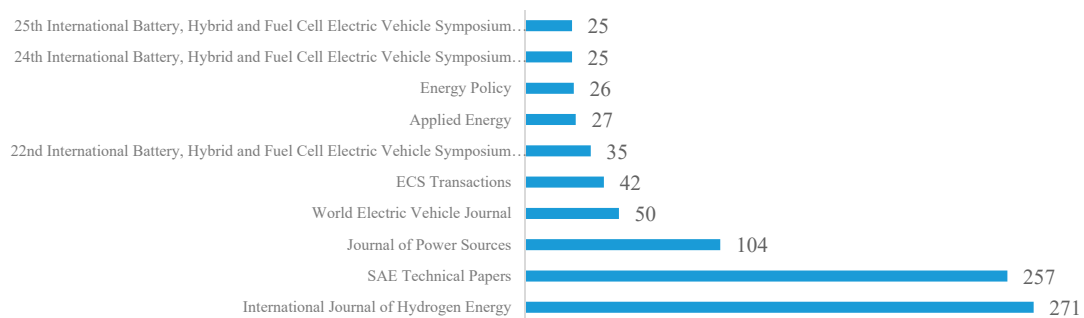


Figure 6. A summary of publications according to the top journals.

According to Scopus, the publications can be categorized into four general areas, which are further divided into 27 major subject areas [43]. With regard to the research fields for the identified publications, they are categorized into a total of 21 specific areas, and these are primarily the areas of Engineering (67.3%), Energy (40.6%), Environmental Science (16.3%), Physics and Astronomy (14.7%), and Computer Science (7.8%).

### 3.1.4. Research Topic

Keywords represent the knowledge hubs of academic studies; therefore, the analysis of keywords can help to identify the leading and developing topics in the research field of FCEVs. A total of 3263 keywords (author keywords) were extracted from 2514 publications by using Vantage Point. The maturity level of those data can be determined by analyzing the first year in which a term in the analysis data set appears. In the case of the analysis of the authors’ keywords, two growth phases are identified

(See Figure 7). The first phase can be called the growth phase between the years 1999–2010, and the second phase, maturity, between the years 2011–2019, can be considered as a stage of continuous downturn and growth, in which the appearance of new study terms is very important.

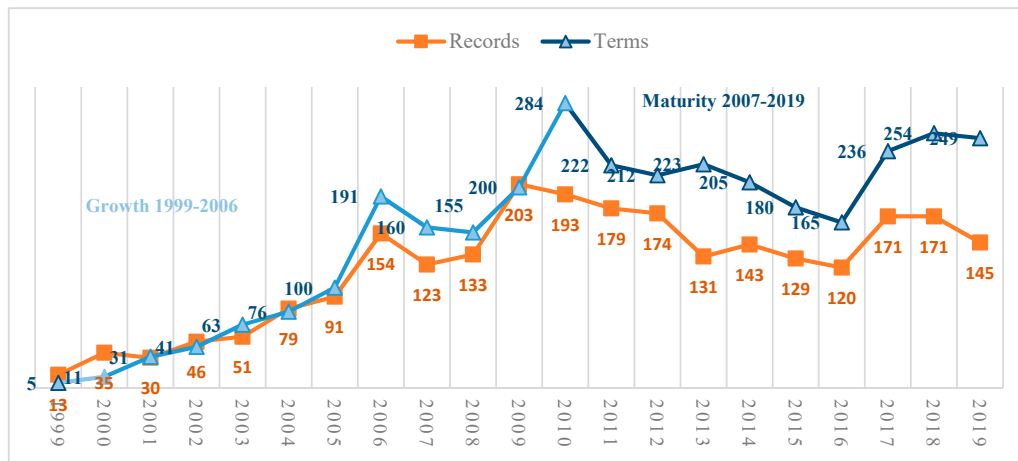


Figure 7. Number of new author’s keywords in any year vs. the number of records of that year.

In addition, the co-occurrence network of authors’ keywords that co-occur at least five times was plotted by using Gephi. The analysis was carried out using a dynamic matrix of co-occurrences, which made it possible to analyze the evolution of keywords in the period 1999–2019. In order to analyze the current situation and to be able to deduce a future trend of the research topics, Figure 8 shows the keyword networks for the 2018–2019 period. In this network, the three most important clusters define the three areas of action in which research science is currently working: FCEVs as a technological development to improve the environment or reduce GHG emissions, batteries and energy management systems, and hydrogen production and storage, with a loss of interest in research related to the topic of powertrains.

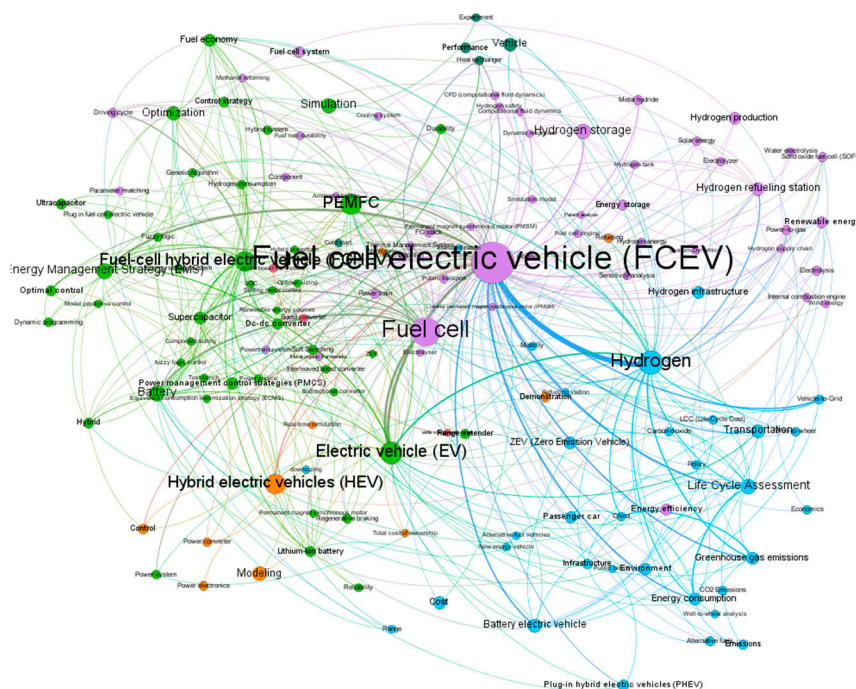


Figure 8. Authors’ keyword co-occurrence networks: 2018–2019 period.

The analysis of these dynamic networks based on the author keywords with the greatest number of co-occurrences allows us to focus on the path followed by research, and also to predict future trends. These research topics have been ongoing for the past twenty years. However, they have evolved until reaching their technological maturity, generating new fields of research related to the main topics. Mainly related to the cluster led by PEMFCs are FC hybrid vehicles, batteries, and energy management systems (EMSs), and to the cluster led by FCEVs: Hydrogen storage/production and Solid Oxide Fuel Cell (SOFC.) As a summary of the analysis in Figure 9, the keyword networks of the periods 1999–2010 (growth period) and 2011–2019 (maturity period) are shown.

#### 3.1.5. Source of Knowledge

In addition, analysis was carried out to identify the five most cited articles in order to be able to detect the origin of the knowledge (See Table 4). These articles were published between 2004–2011; these were years of growth of the scientific development of FCEV technology. However, the results show that China and the USA are the reference countries, and the authors of the most cited articles are affiliated with universities and research entities, such as Harbin Institute of Technology (Wuhan University), Institut National de la Recherche Scientifique, Énergie, Matériaux, and Télécommunications, and Los Alamos National Laboratory. Nevertheless, only one of the most cited articles was made in collaboration between different organizations from different countries (USA and Canada). As far as sources are concerned, the most cited articles were published in IEEE Proceedings, which covers technical developments in electronics, electrical and computer engineering, and computer science, and in Energy and Environmental Science, which is related to energy conversion and storage, alternative fuel technologies, and environmental science.





**Table 4.** Most cited articles: Where knowledge comes from.

Times Cited	Title	Publication Year	Authors	Organizations	Country	Source	Author Keywords
1107	The state of the art of electric, hybrid, and fuel cell vehicles [5]	2007	Chan, C.C.	International Research Centre for Electric Vehicles, University of Hong Kong/Wuhan University	China	Proceedings of the IEEE	Fuel-cell electric vehicle (FCEV) Electric machines Electric vehicle (EV) Modeling Hybrid electric vehicles (HEV)
1021	Recent advances in non-precious metal catalysis for oxygen-reduction reaction in polymer electrolyte fuel cells [54]	2011	Jaouen, F. Proietti, E. Lefèvre, M. Chenitz, R. Dodelet, J.-P. Wu, G. Chung, H.T. Johnston, C.M. Zelenay, P.	Institut National de la Recherche Scientifique, Énergie, Matériaux and Télécommunications/Materials Physics and Applications Division, Los Alamos National Laboratory	United States      Canada	Energy and Environmental Science	Fuel-cell performance * Fuel-cell vehicles * metal catalysis *   Cathodes *
591	Atmospheric science: Cleaning the air and improving health with hydrogen fuel-cell vehicles [55]	2005	Jacobson, M.Z. Colella, W.G. Golden, D.M.	Stanford University	United States	Science	Electrolysis * Hydrogen Fuel-cell vehicles* Air quality *
557	A new ZVS bidirectional DC–DC converter for fuel cell and battery application [56]	2004	Peng, F.Z. Li, H. Su, G.-J.  Lawer, J.S.	University of Michigan Florida State University Oak Ridge National Laboratory  University of Tennessee	United States	IEEE Transactions on Power Electronics	Fuel-cell electric vehicle DC–DC converter Power generation ZVS Auxiliary power supply
532	Electrochemistry and the future of the automobile [57]	2010	Wagner, F.T. Lakshmanan, B. Mathias, M.F.	General Motors Research and Development	United States	Journal of Physical Chemistry Letters	Automotive applications * Li-ion batteries * Hydrogen infrastructure *

\* These articles only have the Indexed Keywords registered. Times cited: Data according to the Scopus database.

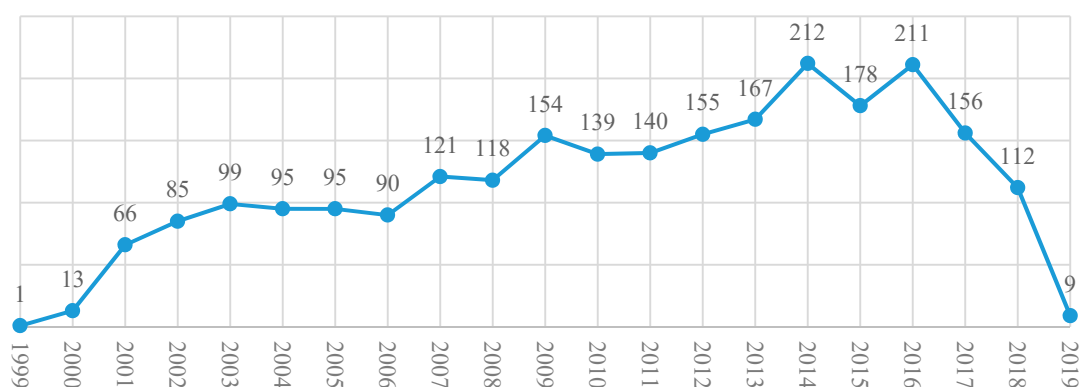


### 3.2. Technological Profile in FCEVs

#### 3.2.1. General Trends

Technological trends were analyzed by using the patent data. For this, Lens.org was used, as it is a global patent database that includes European Patent Office (EPO), United States Patent and Trademark Office (USPTO), World Intellectual Property Organization (WIPO), and Australian patent data collections. The search was carried out based on patent families. A patent family (PF) is a collection of patent applications covering the same or similar technical content. For the period from 1999 to 2019, a total of 1909 PFs were detected.

First, it is interesting to answer the questions: When did the invention publication take place? Who is inventing it? Who is its beneficiary? What is the framework for commercial foresight? What other fields of technological application do these patents cover? The production of patents is low up until 2000, but in the period from 2001 to 2016, technological development is in constant growth (see Figure 10). It is to be expected that there are not many patents in the years 2018 and 2019 because the search was made by the earliest priority year, and the patent applications are normally published 18 months after the date of filing or the earliest priority date, so patents filed in 2018 and 2019 may not have been published yet.



**Figure 10.** The number of fuel-cell electric vehicle (FCEV) patent families by publication year.

#### 3.2.2. Inventive Performance: Inventors, Applicants, and Countries

In order to reflect inventive performance, the top inventors are from South Korea, Japan, and the USA, and their main applicants are automotive companies (See Table 5).

**Table 5.** Who is inventing?

Number of Patent Family (PFs)	Inventors	Main Applicants
37	KWON SANG UK	Hyundai Motor Co LTD
35	TABATA ATSUSHI	Toyota Motor Corp.
33	BORRONI-BIRD CHRISTOPHER E	General Motors Corp.
33	VITALE ROBERT LOUIS	General Motors Corp.
33	HIBIKI SAEKI	Honda Motor Co LTD
32	CHERNOFF ADRIAN B	General Motors Corp.
32	SHABANA MOHSEN D	General Motors Corp.
27	KENJI UYAHARA	Toyota Motor Corp.
25	KOTA MANABE	Toyota Motor Corp.
19	WALTER MARKUS	Daimler AG
18	KERETLI FAHRI	Renault SA

The holder of the legal rights and responsibilities on a patent application is called the assignee or applicant. It can be an individual, a corporation, a university, a hospital, or a government entity. Therefore, if we analyze the applicants, we can see who the beneficiary of the invention is. The top patent-generating organizations are presented in Table 6. Toyota Motors Corp. (JP) has the most PFs, 360, Honda Motors (JP) follows with 210 PFs, and, in the third position, Hyundai Motors (SK) with 175 PFs. In short, the main applicants are companies from the automotive sector or auxiliary automotive sector. In order to determine the market allocation strategy of companies (what is the framework for commercial foresight?), the main countries where patents are protected were identified. The USA dominates with 1583 PFs, the second most PFs come from Germany with 1147 PFs, and Japan has the third most with 1095 PFs.

Table 6. Main applicants and main jurisdiction countries.

Applicants		Countries	
Number of PFs	Applicants	Number of PFs	Jurisdiction Country
360	Toyota Motors	1583	USA
210	Honda Motors	1147	Germany
175	Hyundai Motors	1095	Japan
160	Daimler AG	928	WIPO
103	GM Global Tech Operations Inc.	838	China
92	Nissan Motors	552	EPO
62	General Motors Corp.	413	South Korea
57	Bosch GMBH	192	Canada
56	Kia Motors Corp.	88	France
55	Ford Global Tech Llc.	58	Great Britain

As far as technological cooperation between applicants and inventors is concerned, an applicant collaboration network and co-inventorship network were generated and plotted by using Gephi, as shown in Figures 11 and 12, identifying a collaboration network for the top applicants and top inventors (inventors and applicants with at least five patents in collaboration).

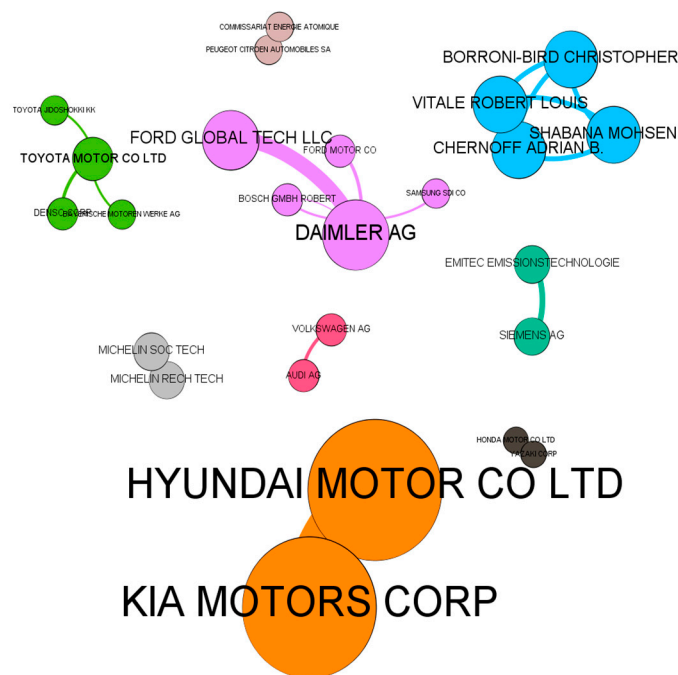


Figure 11. Collaboration networks of applicants.

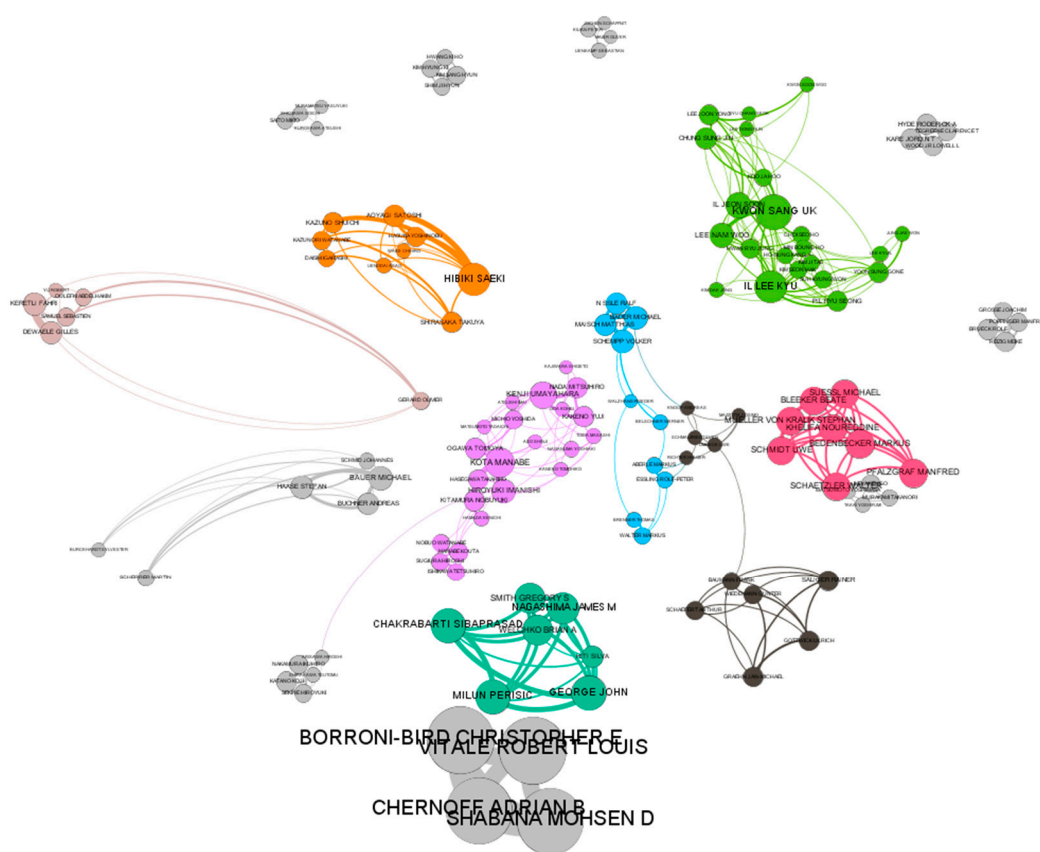


Figure 12. Collaboration networks of inventors.

As far as collaboration between applicants is concerned, the collaborative work takes place between automotive sector companies (from the same business group) and associated research centers. This highlights the relationship between Daimler (Germany), Ford Global Technology (USA), and the Borroni-Bird working group (top inventor) as applicants. With regard to inventors, the collaborations are clustered by country and applicants.

### 3.2.3. Technology Classification

As regards the technological fields where the inventions are being developed (what other fields of technological application do these patents cover?), to determine the approach of R&D efforts in FCEVs, the Cooperative Patent Classification (CPC) was analyzed. The CPC is a joint undertaking between the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO) to merge their classification systems into a single system, which has a similar structure to that of the International Patent Classification (IPC) administered by the World Intellectual Property Organization (WIPO) [58], which provides the invention category and standard information on their technological singularity (World Intellectual Property Organization (WIPO), 2018), enabling the main key items of FCEV inventions to be identified.

In addition to the technological field (Y02T90/34) in which the patent search was carried out, the results display that the other most common CPCs for FCEV patents are based on arrangements for controlling a combination of batteries and fuel cells (B60L58/40) with 893 PFs; the electricity domain in processes related to fuel cells in motive systems (H01M2250/20) is with 791 PFs (see Table 7). Within the top 10 classes, the remaining most common IPCs are related to fuel cells in electrically propelled vehicles (B60L) and to new technological developments for climate change mitigation (Y02T).

**Table 7.** Main Cooperative Patent Classifications (CPCs).

Number of PFs	CPC	Definition
893	B60L58/40	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES—Methods or circuit arrangements for monitoring or controlling batteries or fuel cells, specially adapted for electric vehicles—for controlling a combination of batteries and fuel cells
791	H01M2250/20	ELECTRICITY—BASIC ELECTRIC ELEMENTS—PROCESSES OR MEANS, e.g., BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY—Fuel cells in motive systems, e.g., vehicle, ship, plane
785	Y02T90/32	GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS—TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE—CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION—Fuel cells specially adapted to transport applications, e.g., automobile, bus, ship
595	B60L58/33	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES—Methods or circuit arrangements for monitoring or Controlling batteries or fuel cells, specially adapted for electric vehicles—by cooling
558	B60L58/30	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY—PROPELLED VEHICLES—Methods or circuit arrangements for monitoring or controlling batteries or fuel cells, specially adapted for electric vehicles—for monitoring or controlling fuel cells
447	B60L50/72	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES—Electric propulsion with power supplied within the vehicle—Constructional details of fuel cells specially adapted for electric vehicles
402	Y02T10/7077	GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS—TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE—CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION—Road transport of goods or passengers—on board the vehicle
380	Y02T10/705	GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS—TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE—CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION—Road transport of goods or passengers—Controlling vehicles with one battery or one capacitor only
376	B60L58/34	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES—Methods or circuit arrangements for monitoring or controlling batteries or fuel cells, specially adapted for electric vehicles—by heating
320	B60L1/003	PERFORMING OPERATIONS; TRANSPORTING—VEHICLES IN GENERAL—PROPULSION OF ELECTRICALLY-PROPELLED VEHICLES—Supplying electric power to auxiliary equipment of vehicles—to auxiliary motors, e.g., for pumps, compressors

## 4. Discussion

### 4.1. Science Research Profile: The Situation within the Scientific Research Community

Scientific production related to FCEVs has remained constant for the last ten years. In contrast, the citation of these publications has skyrocketed, so these publications are an important source of

knowledge from other research articles. This frequency of citations is a good indicator of the importance and quality value of the documents [59]. This good indicator opens the door to future research that analyzes whether this research is feeding a new FCEV field of knowledge studies or being directed to other fields of research.

In addition, the citation analysis allows us to identify the most influential publications that should be considered as important conveyors of knowledge [60]. In this case, the most cited publication reflects the state-of-the-art of electric vehicles in general, published in a technical source (Proceedings of IEEE). However, the second most cited article investigates a technical procedure in fuel cells and has been developed in collaboration between two research centers in the USA and Canada, published in a scientific journal (Energy and Environmental Science). The main sources of knowledge originate in China and USA, and it should be noted that only the second most cited publication was produced in collaboration between two countries, the USA and Canada.

In the analysis of all scientific research, the USA is the leading country, supported by its large automotive industry (Ford, General Motors) and its important research centers (Argonne National Laboratory, National Renewable Energy Laboratory, and US Department of Energy). Followed by China, these countries are placed in the central positions of the networks and their collaborations follow the same patterns as in other applied sciences, the great powers of science being centralized, which in turn collaborate with other countries located in the tri-polar world [52]. Moreover, according to Gui et al. [61], the number of countries that are present in the collaboration network is gradually increasing, creating new connections between countries, which can lead to a shift in the center of gravity, with the countries that so far have not been in the central core being drawn closer to it and, therefore, acquiring a greater capacity for collaboration. This opens the door to future new research on the trends of scientific collaboration networks.

The most active organizations are Chinese, most notably the University of Tsinghua, whose results are led mainly by the Ouyang, M. research group, which has the greatest impact, and also represents an important focus on the international collaboration network (see Figure 6), which adds greater transfer to their knowledge. The growing trend and the important role of international collaboration in the increase of scientific production in China have been confirmed from several perspectives [62–66]. However, with Tongji University, despite being the most productive, its publications do not have a great impact on the scientific community.

A large part of the scientific development relating to FCEVs is being carried out by the automotive industry and research centers. This research marks the preliminaries that, a posteriori, will become the patentable technological applications. Therefore, most scientific publications are garnered from two sources: “International Journal of Hydrogen Energy” and “SAE technical Papers” whose publications have a very technical content, and are therefore aimed at future technological development.

Forecasting using a growth curve method is beneficial for estimating the level of technological growth [67]. Therefore, through the technological S-Curve method, Chen et al. [41] conclude in their study published in 2011 that the three main fuel-cell technologies (PEMFC, SOFC, and Direct Methanol Fuel Cell (DMFC)/Direct Alcohol Fuel Cell (DAFC) are in their maturity phase. The same conclusion that is obtained in this study, the analysis of new terms defined by year allows us to conclude that the growth curve has been in its state of maturity since 2010. The temporal analysis of the research topics defines two main fields of research: Hydrogen and its productive management and storage (where SOFC technology is included), and the development of the energy-electrical part for the propulsion of these vehicles (where PEMFC technology is included). In this case, DMFC is not an important research topic, so it does not appear in the network. However, it seems that it is not enough to put this type of vehicle onto the market, and that perhaps it needs governmental support with adequate policies to ensure implementation, among other things.

Having identified the most influential organizations and authors in scientific developments related to FCEVs, and in order to optimize the new research paths, it would be useful to identify the research topics of these actors by analyzing the networks. Furthermore, in order to identify similarities between



authors and to map the scholarly structure [68,69], which would favor the creation of new collaborative synergies, it would be of interest to carry out a co-citation analysis.

#### 4.2. Technological Profile: The Situation within the Industrial Applications

According to classical innovation theory [70,71], scientific publications will hopefully begin to decline in favor of a rise in technological activity or patents, moving from the research phase to the prototype and then to commercialization. As this case study shows, science reaches its fullness in 2009 and then begins to retreat; in turn, the largest number of patents published is produced a posteriori, during the period 2014–2016, but applied some eighteen months earlier, representing inventions or prototypes developed during the period 2012–2014.

China is one of the biggest research powers, and this knowledge is being developed in universities, but it is not as formidable in the innovation process. Although new innovation policies in China were predicted to convert it into a major patent-producing power [72], in the case of FCEVs, this has not happened. Technological advances are still concentrated in universities, contrary to what happens in the main producer countries (USA, Japan, and South Korea) whose technological developments are being carried out in the automotive industry. The collaborative networks also indicate an important degree of relationship between car manufacturers and their research centers, moving towards a field of application relating to powertrain technologies and sustainability.

Nonetheless, promising future vehicle propulsion technology is rather vague. There are still a number of technical barriers holding FCEVs back from the marketplace. Despite the scientific and technological progress made in recent years, this has not been enough to put a marketable product on the market. According to Borgstedt et al. [6], an influential factor may be the high degree of technological complexity, as well as the infrastructures necessary for refueling stations, plus the great advances made in other technologies related to Internal Combustion Engine Vehicles (ICEVs) and Hybrid Electric Vehicles (HEVs). After observing, among other things, certain coincidences between the increases in scientific–technological development and initiatives that stimulate innovation, such as the zero-emission vehicle legislation or the Kyoto protocol, and that the abrupt fall in the number of patents has occurred at times of unstable investment or financial uncertainty, Haslam et al. [72] recommend helping the transition occur: Developing new indicators related to the Kyoto protocol, “design complexity” analysis to identify technical bottlenecks, re-assessing the triple-helix innovation that promotes disruptive technologies, and analyzing new methods for producing hydrogen. The results of this research allow us to affirm that the scientific community has continued to investigate sustainability policies linked to topics such as zero-emission vehicles and greenhouse gas emissions, as well as the production of hydrogen. However, it is also true that most work has continued to be directed at topics more closely linked to the technological development of FCEVs, such as elements directly linked to the propulsion of this type of vehicle, such as PEMFC, SOFC, and DMFC technologies, among others. Likewise, bibliometric and patent data analyses respond to a model that has reached fullness, a technological development carried out, relatively, in international collaboration and that is beginning to regress at the technological level (patents), despite being in a more stable financial situation; even so, we have not reached the commercial goal. Therefore, the discussion now is, has this research been directed judiciously enough to obtain the necessary technological capacity to put FCEVs on the market? Is this destroying a great technological advance that would otherwise provide significant headway in climate change? Do we need new policies that favor its entry into the market?

Relating to the interactions between science and technology, it is important to identify the link between a patent and academic research. A patent document cites both patents and scientific articles, which serve to justify technological development. These scientific articles cited in patents are also known as Non-Patent Literature (NPL), and are defined by the applicant and, in some cases, by the patent examiners, depending on the country. Furthermore, these references become the direct relationship between technological and scientific knowledge, and, therefore, NPL is considered an important indicator of the scientific impact on technological development (patents), making it possible

to measure the transfer of knowledge between science and technological developments [73–76]. This opens the way for future research to analyze the research areas covered by the NPL of identified FCEV patents, and thus to identify the knowledge gaps between science and technology.

## 5. Conclusions

A wide range of technologies linked to a more sustainable transport sector are being developed. Some of them have managed to penetrate the global market, as is the case of the hybrid vehicle and battery electric vehicle, and others, however, are still in the pipeline, as is the fuel cell vehicle. Therefore, this bibliometric and patent data study allows us to see what has happened in the last twenty years. The data obtained have made it easier to identify who the main agents involved in both scientific and technological research are, as well as to reveal their collaborative relationships. At the same time, in order to ascertain where the scientific–technological development has been heading, the main research topics and technological fields have been identified. Its evolution has allowed us to conclude that an important research path has been established, opening new horizons over the years, which has given way to technological development intrinsically linked to technological development related to the propulsion of electric vehicles, but that has failed to reach the market. Providing solutions to this problem, in addition to those already discussed in this paper, future research frameworks related to detecting bottlenecks occurring for commercial development may be proposed: Studying the research programs led by the European Commission (CORDIS) and the US Government (National Science Foundation (NSF)) concerning FCEVs, making a predictive model of technologies in order to forecast their future, performing forecasting studies to study the lifecycle stage of a specific technology, or deeper analyses into which technologies have not reached a state of maturity and to detect if they are key.

Overall, the above topics summarize the main research into FCEV technology, which advances our understanding of this knowledge. As a result, an integrated knowledge map is presented in Figure 13.



Figure 13. A knowledge map of FCEV.

**Author Contributions:** Conceptualization, I.A.-M. and R.M.R.-B.; methodology, I.A.-M., E.Z.-B., and G.G.-A.; software, I.A.-M.; validation, I.A.-M., R.M.R.-B., and E.Z.-B.; formal analysis, I.A.-M.; investigation, I.A.-M. and G.G.-A.; data curation, I.A.-M.; writing—original draft preparation, I.A.-M.; writing—review and editing, I.A.-M.; visualization, I.A.-M.; supervision, E.Z.-B., G.G.-A., and R.M.R.-B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

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