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A Review on Hydrogen and Fuel Cells in Transportation Science and Technology Studies: A Bibliometric Analysis

Ulaştırma Bilimi ve Teknolojisi Çalışmalarında Hidrojen ve Yakıt Hücreleri Üzerine Bir İnceleme: Bibliyometrik Analiz

Metin YILDIRIM[1]

ABSTRACT

Current transportation systems face numerous issues, including the reduction of carbon emissions, noise pollution, and other pollutants. These concerns mainly stem from escalating environmental and economic issues across society. These constraints have compelled many researchers and business owners in the transportation sector to seek cleaner, more efficient, and more sustainable alternatives. Recently, the transportation sector has increasingly focused on hydrogen and fuel cells as key areas of research. The article aims to identify the main themes in the research on hydrogen and fuel cells within the field of transportation science and technology studies, using bibliometric analysis. VOSviewer was employed to evaluate 984 articles related to hydrogen and fuel cells under the Transportation Science Technology category from the Web of Science database. The literature was examined in terms of annual trends in publications, research institutions, and leading journals. Core topics and focal areas were identified through literature co-citation analysis and keyword co-occurrence clustering analysis, providing a comprehensive overview of the current and future state of the field and its research directions. According to our findings, research from 2020 to 2025 accounts for nearly half of all research. China has the most publications, the United States is the primary center in the co-authorship network map of countries, DOE is the institute with the most publications, IEEE is the highest volume publisher, and seven clusters were identified in the cluster analysis performed on keywords.

Keywords: Fuel cell, Hydrogen, Bibliometric Analysis, Co-Occurrence Analysis, Network Analysis

ÖZ

Mevcut ulaşım sistemleri, karbon emisyonlarının, gürültü kirliliğinin ve diğer kirleticilerin azaltılması da dahil olmak üzere çok sayıda sorunla karşı karşıyadır. Bu endişeler esas olarak toplum genelinde artan çevresel ve ekonomik sorunlardan kaynaklanmaktadır. Bu kısıtlamalar, ulaşım sektöründeki birçok araştırmacıyı ve işletme sahibini daha temiz, daha verimli ve daha sürdürülebilir alternatifler aramaya zorlamıştır. Ulaşım sektörü, hidrojen ve yakıt hücrelerine temel araştırma alanları olarak odaklanmaya başlamıştır. Makale, bibliyometrik analiz kullanarak ulaşım bilimi ve teknolojisi çalışmaları alanında hidrojen ve yakıt hücreleri araştırmalarındaki temel konuları belirlemeyi amaçlamaktadır. Ulaştırma Bilimi Teknolojisi kategorisi altında hidrojen ve yakıt hücreleriyle ilgili Web of Science veritabanından 984 makaleyi değerlendirmek için VOSviewer'ı kullanilmistir. Literatür, yayınlardaki, araştırma kurumlarındaki ve önde gelen dergilerdeki yıllık değişimler açısından incelenmistir. Ana konular ve odak alanları, literatür eş atıf analizi ve anahtar kelime eş oluşumu kümeleme analizi ile belirlenerek konunun mevcut ve gelecekteki durumu belirlendi ve araştırma konularına ilişkin kapsamlı bir genel bakış sağlanmıştır. Araştırma sonuçları, 2020-2025 yılları arasındaki yayınların tüm yayınların neredeyse yarısını oluşturduğunu; en fazla yayının Çin'de yapıldığını, ülkelerin ortak yazarlık ağı haritasında birincil merkezin ABD olduğunu, en fazla yayına sahip kurumun DOE, en yüksek hacimli yayıncının IEEE olduğunu ve anahtar kelimeler üzerinden yapılan küme analizinde yedi küme tespit edildiğini ortaya koymaktadır.

Anahtar Kelimeler: Ağ Analizi, Bibliyometrik Analiz, Eş Zamanlılık Analizi, Hidrojen, Yakıt Hücresi.

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INTRODUCTION

The increasing awareness regarding greenhouse gas emissions and their effects has highlighted transportation as an important focus for mitigation strategies, accounting for 15% of anthropogenic greenhouse gas emissions, 23% of energy-related emissions, and 8.7 Gt CO_2-eq emissions [Ferrer & Thome, 2023, p. 1]. Mitigating carbon emissions is a critical aspect of combating global warming. Advancements in the transportation industry are recognized as critical contributors in mitigating greenhouse gas emissions. There has been a significant increase in studies about the transportation industry due to environmental factors. [Wang et al., 2020, p. 1]. The Paris Agreement aims to restrict global warming to a maximum of 1.5 °C above pre-industrial levels, thereby altering the framework for policy-relevant research and presenting a challenge to the intergovernmental panel on climate change and researchers [Hulme, 2016, p. 222]. In transportation, a proposed method to globally reduce greenhouse gas emissions is developing and implementing cleaner technology [Vilchez & Jochem, 2020, p. 1]. Most research efforts are concentrated on electric vehicles and their associated technologies to reduce emissions that the transportation industry generates.

Electric cars are classified into five categories based on engine technology: Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs), Fuel Cell Electric Vehicles (FCEVs), and Extended-Range Electric Vehicles (ER-EVs). PHEVs and HEVs will be identified with the hybrid vehicles categorization, while BEVs, FCEVs, and ER-EVs have been categorized as all-electric cars[Taghizad et al., 2023, p. 9]. Each of the five technologies mentioned in both the hybrid and all-electric groups has its own benefits and features that make them better for driving electric vehicles on a range of terrains [Sanguesa et al., 2021, pp. 376–377].

PHEVs combine an internal combustion engine, an electric motor, and a battery. PHEVs may be powered externally, and an internal combustion engine is used when needed. PHEVs do not negatively impact the environment while operating in all-electric mode [Singh et al., 2021, p. 59].

HEVs are distinguished not only by the fact that they employ an internal combustion engine to generate energy, which either powers the electric drive motors directly or charges the batteries, but also by the fact that the batteries in HEVs cannot be recharged by external power sources [Kebriaei et al., 2015, p. 299].

BEVs are entirely electric and depend only on substantial battery packs for propulsion. FCEVs have an electric motor. The motor has been driven by a compressed combination of hydrogen and oxygen. Water and heat are the two major byproducts that the motor has been generating (Vengatesan et al., 2024, p. 1]. ER-EVs are similar to BEVs. ER-EVs differ from BEVs primarily in that they include an auxiliary combustion engine. The engine just recharges the battery as required. The mechanism contributes to an increase in range.

The assessment of FCEVs' advantages over other electric vehicle technologies in relation to four main items. The first item is emission. FCEVs generate water as a primary byproduct, leading to zero emissions [Daud et al., 2011, p. 262]. FCEVs are seen to be in a significantly advantageous position when comparing the emission values produced by both internal combustion engine vehicles and hybrid electric vehicles due to their dependence on fossil fuels. The second item is that FCEVs. FCEVs' driving ranges are often greater driving ranges than BEVs. Hydrogen fuel's have higher energy density compared to batteries. This allows for greater travel distances without frequent refilling. [Aminudin et al., 2023, p. 4384]. The third item is refueling. FCEVs resemble the refueling process of an ordinary gasoline car. FCEVs have a major advantage over BEVs in terms of charging times. [Sahin, 2024, p. 604]. The last item is heavy-duty applications. FCEVs are appropriate for heavy-duty

applications. Hydrogen fuel is a more suitable choice for vehicles that require a higher level of power due to its high energy density.[de las Nieves Camacho et al., 2022, p. 29516].

Bibliometric methods have been used to substantiate historical theories on the evolution of disciplines [Raina & Gupta, 1998]. Bibliometric analysis assists in the identification of connections between policy changes and scientific development [Machado et al., 2016]. The collaborative structure of an interdisciplinary field can be investigated through bibliometric analysis [Liu & Xia, 2015]. Previous studies have shown a strong association between cooperation and research output, as well as between collaboration and financial research support. The degree of cooperation cannot be readily assessed by conventional surveys and observational techniques. Bibliometric analyses give an effective technique to analyze collaboration in research[Subramanyam, 1983]. Bibliometric analysis is a technique for visualizing and evaluating literature's quantitative relationships and distribution structures via statistical and mathematical theories grounded on the features of literature aspects [Van Eck & Waltman, 2014]. Researchers can predict research deficits by identifying significant topics that are of interest to scientists in the field through the use of bibliometrics tools [Tan Luc et al., 2022].

Co-citation analysis is an extensively utilized technique in bibliometric studies. Co-citation analysis evaluates the frequency with which contributions have been cited in conjunction. Assuming that writers often quoted together connect with the same intellectual tradition. Co-citation patterns facilitate the identification of connections among the most significant works, the exploration of subfields, and the assessment of interconnections [Calabretta et al., 2011, p. 500:501].

Co-citation analysis assesses the frequency of simultaneous citations of contributions. Co-citation patterns enable the identification of relationships among the most prominent works. Keyword co-occurrence analysis examines the strength of correlations between words by investigating their simultaneous presence throughout an extensive corpus of texts. The main aim is to clarify the internal linkages and structure, as well as to reveal the study horizons of an identified academic at the heart of the matter. The research frontier encompasses fundamental issues, with the growth of theoretical trends and novel themes. It is possible to make accurate predictions about the future tendencies of evolutionary study by taking into account the existing state and hot spots for research.

A citation analysis objectively identifies prominent publications within each discipline and analyzes the relationships between citations or co-citations of analytical subjects, including sources, documents, and authors[Hota et al., 2020]. Both the significance of the research to the area of study and the standing of the researchers themselves may be inferred from the total number of citations that are included within the entire body of publications.

The citation network emphasizes acknowledged research foundations and changing trends. It highlightes fundamental studies shaping modern area advancements. Combining technological, policy, and computational developments to propel the future of sustainable and intelligent transportation systems, the clustering pattern emphasizes the multidisciplinary character of research.

The distance between elements in the graphic roughly signifies their relatedness within the co-occurrence network. The distance is defined as the spacing between the nodes. In the distance-based methodology, the nodes within a bibliometric network are arranged so that the proximity between two nodes typically reflects their relatedness [Van Eck & Waltman, 2014, p. 288]. In general, the proximity of two items correlates positively with their relatedness based on occurrence connections within the analyzed corpus of publications[Nadzar et al., 2017, p. 98].

A limited number of bibliographic analyses have been used to analyze the scientific literature in transportation science technology studies, mainly on the following topics: Pedestrian safety,

intelligent transportation systems, supply chain resilience and sustainability, agent technology in traffic control and management systems [Chen & Guo, 2014, 2014; Das et al., 2023; Li et al., 2010; Warmbier & Kinra, 2022; Zhao et al., 2017]. The relatively limited amount of research that biblometric analysis has conducted on the study topic shows that there is an important gap. One of the most significant elements about this research is that it will help reduce a gap in the topic that has been researched.

Developments pertaining to hydrogen and fuel cells in transportation science and technology are gaining significance daily. The primary reason for this is the strategic potential of the key technology in reducing the carbon footprint within the transportation industry. The hydrogen and fuel cells have the potential to cause significant developments and transformations in a number of structures, including the industrial ecosystem and supply chain within transportation, in addition to impacting carbon emission values.

Our study uses bibliometric analysis to address the following research questions:

RQ1: What is the historical trend in the number of publications on the researched topic, and how has it developed over the years?
RQ2: Which countries contribute most substantially to the academic output on the researched topic?
RQ3: Which countries collaborate most frequently in the field, and how are they interconnected in the co-authorship network?
RQ4: Which academic or research institutions are the leading contributors to the research topic?
RQ5: Which academic publishers have published the most significant number of articles on the research topic?
RQ6: Which articles have received the highest citations within the research topic?
RQ7: What are the co-citation patterns of the articles within the research topic?
RQ8: What are the most frequently co-occurring keywords?
RQ9: What are the research clusters derived from keyword co-occurrence analysis?

The aim of the research is to help scientists and professionals engaged in or intending to engage in the field of study by providing answers to the aforementioned research questions through a bibliometric analysis on hydrogen and fuel cells in transportation science and technology.

The subsequent parts are arranged below. The Research Methodology section discusses the bibliometric technique and data collection in detail. The Results section provides a visual depiction of the findings and analysis. The Conclusions section provides additional evaluation and emphasizes key results.

A literature search conducted on WOS and Google Scholar did not yield any research on bibliometric analysis concerning hydrogen and fuel cells in transportation. Every research question has significance for addressing a particular gap in the literature. The first research question seeks to provide a complete overview of the evolution of research topic over time. It seeks to address the gap in the literature. The second research question aims to address the geographical distribution deficiency in the literature. The response has pinpointed the countries that assume predominant roles. The response to the third research question fills a gap in the literature on international research networks The fourth research question is to contribute to filling a gap in the literature on research productivity and specialization dynamics at the institutional level. The fifth question seeks to enhance the methodical analysis of publication channels in the literature. The answer has identified the academic journals and publishing houses that disseminate studies. The sixth research question helps to identify details of the fundamental studies that guide the field's scientific development. The seventh research question identifies the publications that receive the most

frequent citations among the conducted studies. It is becoming clear how the information in the literature is organized and what main topics it is based on. The answer to the eigth research question helps us understand which concepts are key to the studies on the research topic and which themes emerge. The last research question is to find out which groupings of common ideas and themes come up in different research on the same topic.

1. Research Methodology

A detailed comparison of bibliometric analysis, meta-analysis, and systematic literature reviews was undertaken. It has conducted to choose the appropriate analysis for the research. One of the main advantages of bibliometric analysis is that it enables comprehensive analysis of bibliographic data. It spotts patterns, intellectual frameworks, and research trends[Donthu. et al., 2021, p. 287]. The second advantage is that it offers objective and systematic analyzing scientific literature analysis. It by combines data from several sources. Compared to systematic literature reviews and meta-analyses, bibliometric analyses reduce researcher bias while increasing rigor [Zupic & Čater, 2015]. Another advantage is its capacity to provide a structural and visual overview of the research topic [Van Eck & Waltman, 2014]. Bibliometric analysis selected in this study because of the unique benefits.

Bibliometric analysis gives an overview of how information is shared. It show the affects on people by measuring different parts of academic communication The quality and reliability of the results are contingent upon the necessity of specific technical skills, the capacity to incorporate diverse analytical methods, and the significance of interdisciplinary collaboration[Celestino et al., 2024, p. 13424:43433). An uncontainable pattern of dynamic growth in bibliometrics as a research methodology was identified through the examination of significant records indexed in the Web of Science-Core Collection from 1965 to 2019. The number of published papers increased by a factor of 12 between 2000 and 2014, involving all domains of knowledge [Koo & Lin, 2023, p. 2]. Bibliometric analysis is predominantly accepted as a valid and reliable analysis that will assist in tracing the progress of a scientific topic and evaluating the research impact of people engaged (Dardas et al., 2019, p. 8]. On the other side, there is a need for standardization in bibliometric research and technology to make bibliometric findings more reliable and valid[Glänzel, 1996].

Certain researchers provided detailed instructions on how to conduct the bibliometric analysis. In general, their contributions are more conceptual than practical. The most effective methods for conducting bibliometric research and the best practices associated with it are still not commonly recognized [Öztürk et al., 2024, pp. 3356–3357]. The validity and reliability of bibliometric indicators continue to be crucial issues in research analysis. Assessing the validity and reliability of bibliometric indicators is crucial for evaluating scientific performance (Nederhof, 1988, p. 194]. The reliability and validity of bibliometric analyses have been a subject of ongoing debate for an extended period. The context and purposes for which they are suitable are still in dispute. Citations and other bibliometric metrics have been proposed as preferable to conventional peer review methods for the purpose of research evaluation. [Aksnes et al., 2019, p. 1]. In order to solve the problem several actions have been taken to resolve the problem. One of the causes of the problem stems from data and databases. The databases often identify research beyond the review's topic, and these extraneous studies undermine the validity of the bibliometric analysis. Incorporating inclusion and exclusion criteria would enhance the bibliometric analysis's validity(Ozturk, 2021, p. 530:531]. Certain academic frameworks have underlined the need for systematic procedures and transparency in bibliometric studies, and a lack of transparency in this situation looks to be a risk to reproducibility, methodological rigor, validity, and reliability[Celestino et al., 2024].

In the Vosviewer study, the co-authorship type of analysis was chosen with countries as the unit of analysis. The co-authorship filter mandated a minimum of 10 papers and 10 citations per country. Out of the 71 countries, 23 met these criteria. The provided image visually depicts the number of articles by country, with the size of the circles directly related to the article count, as well as illustrating the relationships among the articles. Figure 2 illustrates the distribution of countries concerning the subject of the study issue, as well as the collaborative network among them.

VOSviewer was used to evaluate the connection in order to determine the importance of these studies and their primary features. Citation has been selected as the kind of analysis, and authors have been selected as the unit of analysis, respectively. The minimum number of document citations is set to zero, which is the default value in the VOSviewer. Out of 984, all have surpassed the threshold level. Among these 984 papers, only 418 are interconnected.

The study relied on the keywords supplied by the authors of the articles. Keyword co-occurrence analysis relies on the statistical frequency of pairs of keywords in a given dataset. 3.073 keywords were found at the initial face of the research. Thesaurus files were developed to harmonize terms into a single version, including plural and singular, synonyms, abbreviations, and complete terms. Various terms were eliminated, such as analysis methods, generalist phrases, and words. This research concentrates on phrases that occurred a minimum of five times within a curated selection of publications to provide a clear picture. This restricted the keyword set to 75

VOSviewer is a software application that is frequently employed to visualize literature information. The analysis of cluster density and co-occurrence network, which is conducted using literature information, offers a valuable visualization. VOSviewer was created to provide an enhanced display of the mutation detection function [Zhou et al., 2022, p. 4]. Keyword mutation detection is being used to highlight the evolution, research horizons, and developmental trends in hotspots. VOSviewer has been used as the exclusive bibliometric analysis tool in this study.

In bibliometric analysis, the intellectual structure serves as an analytical framework designed to elucidate the knowledge, theoretical underpinnings, and evolutionary trajectories of a certain scientific domain(Chen, 2006, p. 359). Co-citation analysis is one of the primary approaches to uncovering intellectual structure and not only enables thematic clustering of the literature but also helps to discover linkages. Co-citation patterns exhibit substantial divergence from bibliographic coupling patterns; however, they typically align with direct citation patterns. Clusters of co-cited publications provide a novel approach to examining the conceptual structure of scientific disciplines. Co-citation analysis examines how often two research authors or publications have been cited in a single publication [Small, 1973, p. 265]. A deductive method was utilized to name each cluster in this study to find the knowledge base. During this procedure, content analysis was used to look at the articles in the cluster that had the most citations to figure out what the major subject of the cluster was.

The WOS database was the data source used in our bibliometric analysis. WOS is a highly regarded scientific database for its substantial volume of publications and extensive and dependable content. The search string that was utilized was as follows TS = (HYDROGEN OR "FUEL CELL" OR "FUEL CELLS") AND TS= (AUTOMOBILE* OR BIKE* OR BOAT* OR VEHICLE* OR CAR* OR BUS* OR LORRY OR LORRIES OR TRUCK* OR "MOTOR COACH" OR"MOTOR COACHES" OR TRAM* OR TRACTOR*) The research area was restricted to transportation science technology within the Web of Science Categories.

2. Results

The relevant dataset was created and saved on February 15, 2025. The search was conducted in the topic section, which includes the title, abstract, keyword plus, and author keywords sections. The relevant research yielded 1.858 academic studies. The number of data sets subject to the research was reduced to 984 when the search was restricted to articles written exclusively in English. Articles are selected for publication exclusively based on their ability to preserve the academic integrity and high quality of the literature. In order to preserve the integrity of the analysis, publications that were exclusively published in English were included. To enable the bibliometric analysis with VOSviewer software, all documents' complete records and references were exported.

This study employs the chronological and geographical distribution of literature and research methodologies as fundamental frameworks to analyze historical development systematically, research areas of interest, and trends in hydrogen and fuel cells within transportation science and technology studies. It reviews overall growth trends, country and affiliation analysis, publisher analysis, analysis of highly cited articles, co-citation analysis, and keyword co-occurrence analysis. The analysis results in many contributions. It offers an immediate reflection of the present state and substance of hydrogen and fuel cells in transportation science and technology studies, thereby enabling the straightforward tracking of the subject's roots.

The analyses were performed to address the research questions. The following sections reveal the results.

2.1 Publication Trends Over Time

The initial research query was about the trend of literature. It has been addressed by tracing the evolution of hydrogen and fuel cells. The selected field was transportation science and technology. The variation in publication quantity serves as a significant indication of the developmental patterns within a discipline. The distribution of articles across the is shown in Figure 1.

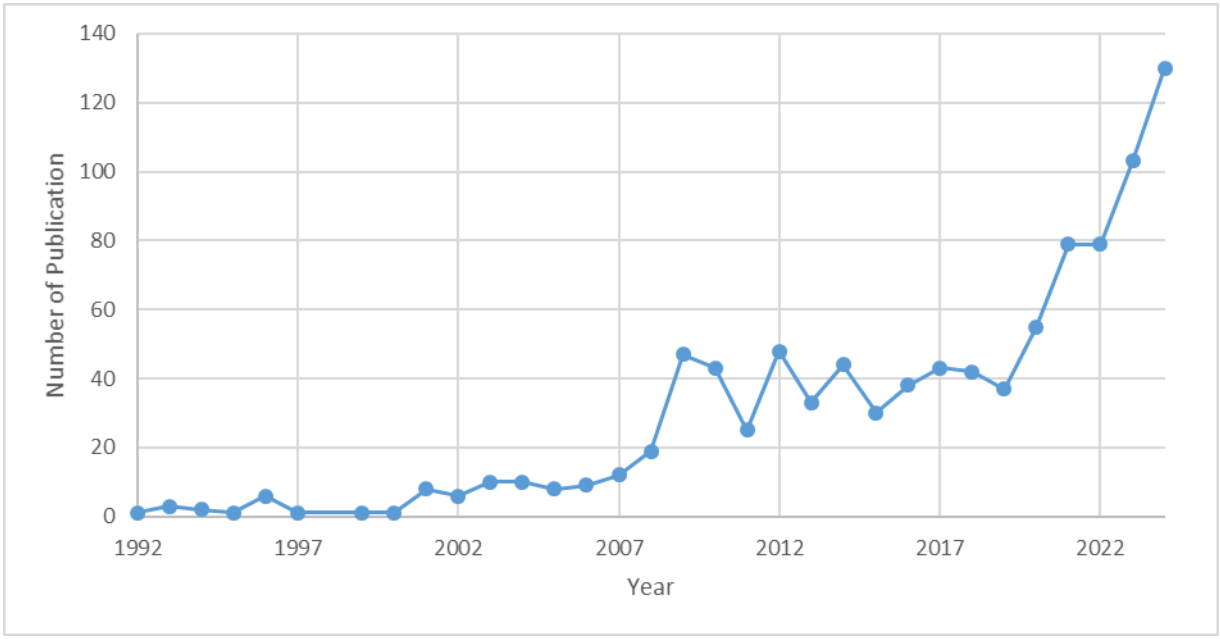


Figure 1. Distribution of the Number of Published Papers

The graph indicates research trend on hydrogen and fuel cell Technologies. It has transitioned from a significant field of study to a primary focus during the last 30 years. The average annual publication was 2-3 in the 1990s. Interest has progressively escalated in the 2000s. It stabilized in the 2010s.

Significant surge transpired in the 2020s. The significant rise in 2023 and 2024 could have been ascribed to global climate targets, the energy crisis, and decarbonization actions. The number of research conducted between 2020 and 2025 is around fifty percent of the total studies since 1992.

2.2 Leading Countries in The Research Topic

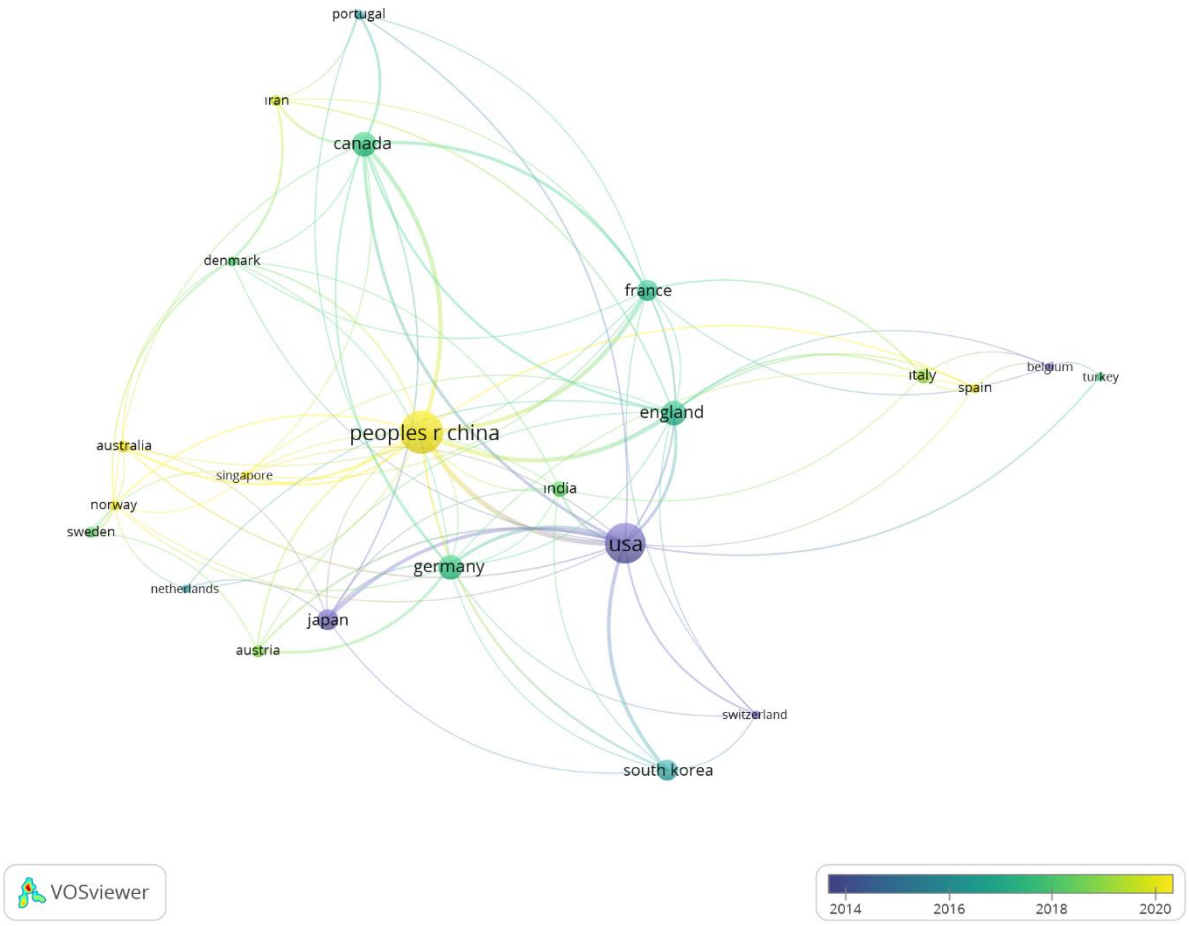
The dataset indicates that publications originated from 72 countries. Table 1 displays the top five countries in research. They were utilized to address the second research question.

Table 1. Top 5 Major Research Countries

Countries	Record Count
China	243
USA	222
Canada	84
England	82
Germany	78

China dominates with a significant 24.16% share of total publications. It reflects its robust research infrastructure and investment. The United States comes next with 22.07%. It shows that it is focused on new ideas and technological advancement. Canada, England, and Germany all contribute a significant number of articles, making up 8.35%, 8.15%, and 7.75% of the total.

2.3 Co-authorship Network of Countries



The analysis of the co-authorship network of countries has been carried out in relation to the third research topic. USA is the primary hub. It has with the most extensive global connections. China, Germany, Japan, Canada, France and England serve as important subsidiary nodes. The temporal color gradient reflects a progression towards more diversified collaborations in recent years. It has established research clusters emerging across European countries. It has an increasing significance among Asian countries.

2.4 Leading Research Institutions

The affiliations of the authors was conducted as part of fourth research question. The top five institutions are shown in Table 2, which is presented below.

Table 2. Top 5 Major Research Institutions

Affiliations	Record Count
United States Department Of Energy (DOE)	33
University Of California System	31
Universite De Technologie De Belfort Montbeliard (UTBM)	29

Affiliations	Record Count
Tsinghua University	26
Centre National De La Recherche Scientifique (CNRS)	24

The affiliation data shows strong government-academic cooperation. It has been driving automotive and energy technology development at the top five universities. Government financing and research are crucial. With 3.28% of connections, DOE leads. Next university is University of California System(3.08%). With vast resources across campuses, it has a significant academic research network. With 2.88%, UTBM ranks third. From an engineering and technology schooll, it has demonstrated significant European contributions. China's Tsinghua University ranks fourth (2.58%). Its expanding scientific significance has been reflected . With 2.39%, CNRS rounds out the top five. Universities and Government research agencies located in Asia, Europe and North America dominate this area. American, French, and Chinese research groups balance have been observed.

2.5 Leading Research Institutions

One of the major signs of solid study quality is the existence of top-tier publishers in the field. Fifth research question answer has been analyzed in this topic. The table below shows the top five publishers based on the number of publications. Table 3 indicates significant concentration. The top five publications have the most influence when it comes to spreading research in this field. IEEE is the top-tier publisher with the most publications.

Table 3. Top 5 Publishers

Publishers	Publications
IEEE	243
Elsevier	199
Sae Int	159
Sage	106
Mdpi	68

2.6 Leading Research Institutions

The citations of the articles in the dataset have been analyzed in the context of the sixth research question. Table 4 below presents the top five publications ranked by citations within the scope of the obtained dataset.

Table 4. Top 5 Cited Articles

Article Title	Authors&Year	Citations	Links
Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric,	(Khaligh & Li, 2010)	854	43

Article Title	Authors&Year	Citations	Links
hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art			
A green vehicle routing problem	(Erdoğan & Miller-Hooks, 2012)	716	5
Constant power loads and negative impedance instability in automotive systems: Definition, modeling, stability, and control of power electronic converters and motor drives	(Emadi et al., 2006)	689	4
Electric vehicles as a new power source for electric utilities	(Kempton & Letendre, 1997)	572	3
Electric, hybrid, and fuel-cell vehicles: Architectures and modeling	(Chan et al., 2009)	520	30

2.7 Co-citation Patterns and Research Domains

The analysis of the co-citations of the articles was carried out in order to provide a response to the seventh research question. In Figure 3 presented below, 418 papers have been identified. In the figure, the weights are determined by citation values. Thirty-two clusters have been identified in the course of research. Articles within the same cluster exhibit similarity in topics of research. These publications provide a knowledge foundation for the research domain, and their findings and methodologies serve as a reference for other academics.

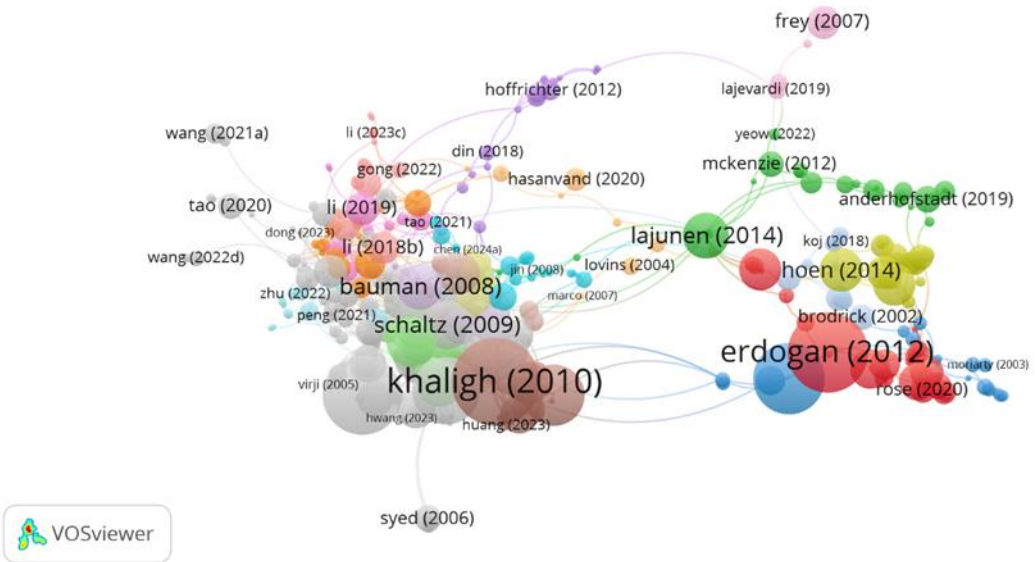


Figure 3 . Visualization of the Co-citation Density

The main clusters and key influential publications that shape research in hydrogen and fuel cells in transportation science and technology are highlighted in the aforementioned Figure 3. The highest citation impact is exhibited by older, foundational works, such as [Khaligh & Li, 2010]and [Emadi et al., 2005], which reinforces their long-term influence on electric vehicle power systems. These studies constitute a critical backbone for subsequent research, serving as anchor points in the citation network.
The study conducted by Khaligh & Li (2010) is referenced in hydrogen and fuel cell research for its eff ective evaluation of various energy storage technologies for electric and hybrid vehicles, and it has be en cited in academic publications in multiple languages, including turkish[Gelen & Tüfekcioğlu, 2020; Hamurcu et al., 2021; Sarıkurt & Balıkçı, 2017; Yapıcı et al., 2024].

Studies by Wang [2022] and Li [2022], among other recent publications, show new trends and an increasing recognition among scholars. Several studies, such as the green vehicle routing research conducted by Erdoğan & Miller-Hooks (2012), emphasize the significance of optimizing alternative fuel vehicle routes in logistics research. [Kempton & Letendre, 1997] and [Chan et al., 2009] are examples of studies that have significantly impacted the development and utilization of EVs.

Recent studies indicate a transition towards intelligent energy management, real-time data analytics, and electrification within commercial transportation sectors. Although their citation counts are relatively modest owing to their recent publication, their position in high-impact journals indicates their potential to influence future research trajectories. The emergence of several 2024 studies indicates increasing progress in transportation electrification, emphasizing the integration of autonomous and electric vehicles, grid interface, and energy-efficient logistics solutions.

2.8 Analysis of Keywords

The next research is conducted in scope 8th research question. co-occurrence patterns of keywords has been analyzed. Table 5 shows the top five terms.

Table 5. Top 5 Keywords by Occurrences and Total Link Strength

Label	Cluster	Occurrences	Total Link Strength
Fuel Cells	3	150	332
Hydrogen	1	105	220
Electric Vehicles	2	87	141
Energy Management	2	77	205
Batteries	2	69	226
Hybrid Electric Vehicles	5	42	93
Energy Storage	4	20	47
Supercapacitor	2	16	33
Electric Bus	4	7	7

Label	Cluster	Occurrences	Total Link Strength
Public Transport	4	5	7

On the analysis of high occurrences and total link strength values, fuel cells, hydrogen, and energy management have signifcantly high values. This is an important indicater for significant research endeavors . The density of keyword occurrences is shown in Figure 4.

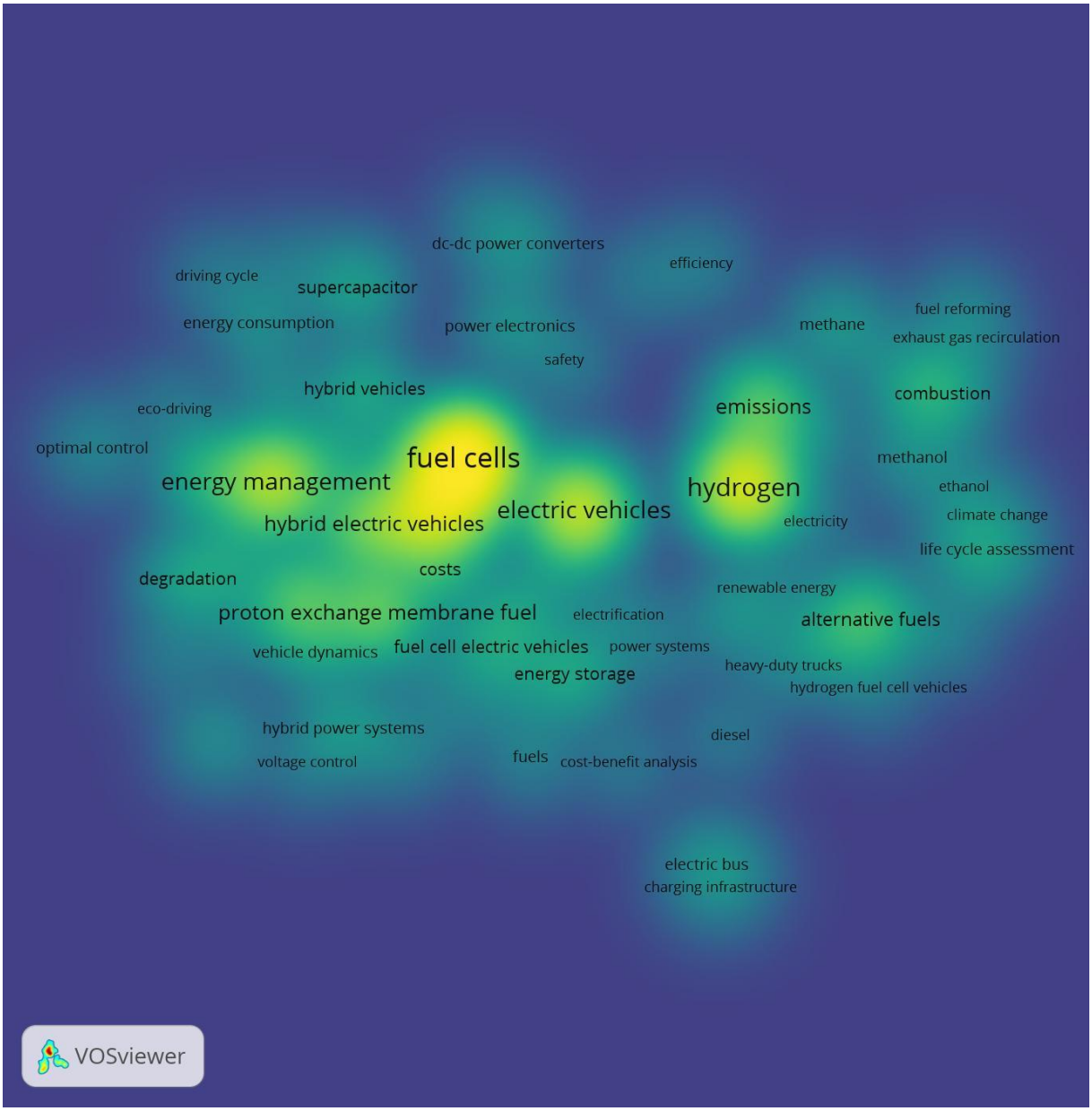


Figure 4. Keyword Density Visualization

Fuel cells, hydrogen, electric vehicles, energy management, hybrid electric vehicles, and batteries positions are at the focal points in the Figure 4. These indicate a decline in fossil fuel. Energy management, cost analysis, and renewable energy sources are prominent terms. this is an indication of that the associated research using these keywords is projected to rise

Figure 6 illustrates a succinct examination of the overlay visualization, whereby node size reflects the frequency of keyword occurrences and color indicates the average publication year. The color overlay, which spreads from purple to blue, represents an older average publication year, primarily between 2014 and 2016. The color of mid-range averages typically ranges from turquoise to green, indicating an average publication year of approximately 2017 to 2019. The final part of the color ranges from yellow-green to saturated yellow, indicating that new publications took place in 2019 and onward.

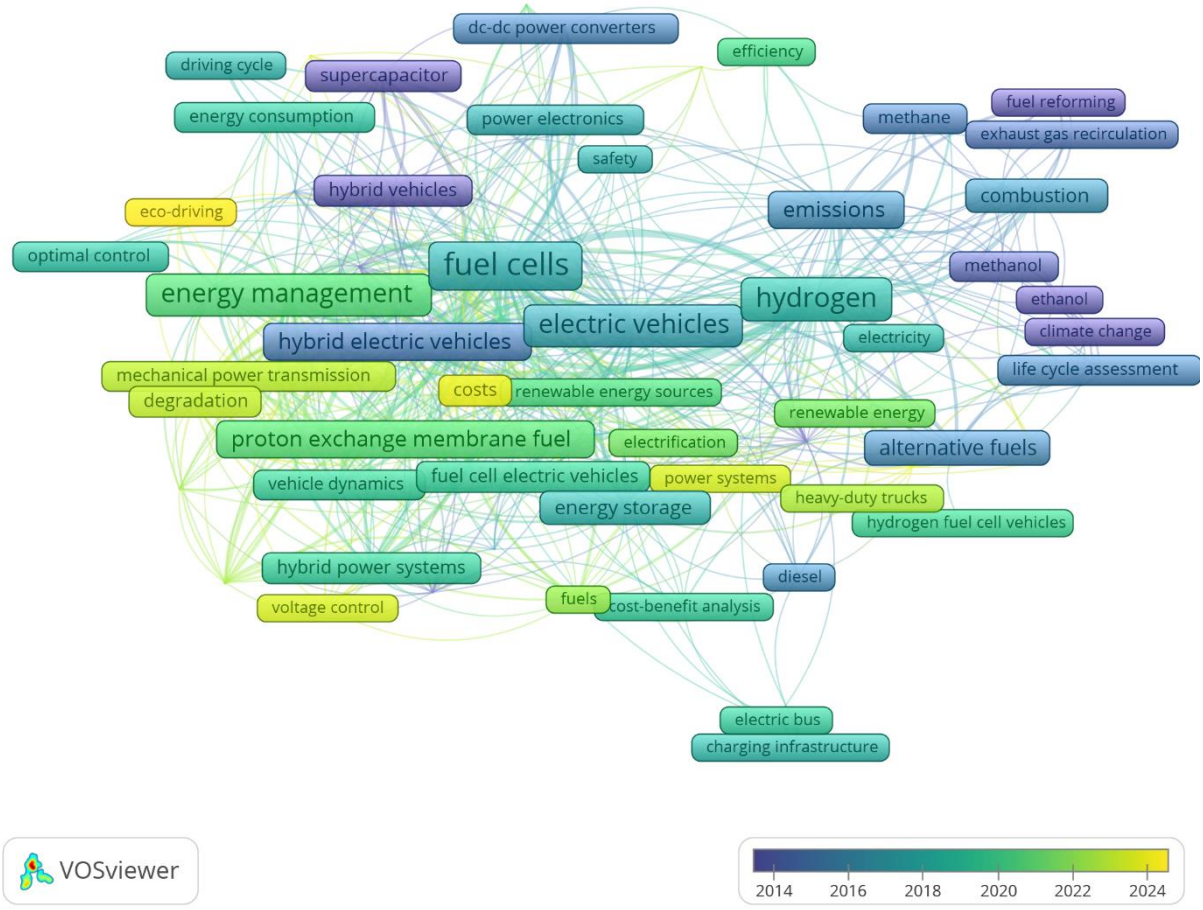


Figure 5. Keyword Co-occurrences Weighted by Occurrences and Colored by Average Publication Year

Analyzing the color of each node revealed crucial phrases, including hybrid electric cars and emissions, which are part of the long-range explored topics. The second group may be categorized as medium-range. The average group has terms such as fuel cells, electric cars, and hydrogen, among others. The popularity of these words emerged some years ago. The last group includes crucial terms such as carbon neutrality, charging infrastructure, electric bus, and cost-benefit analysis, in which their recent average publication year indicates an increase in interest in academia.

Within the scope of the last research question, the findings of the keyword co-occurrence analysis concerning hydrogen and fuel cells in transportation science and technology studies done using VOSviewer software are displayed in Figure 6.

Cluster analysis was performed for the final research question, and seven clusters were identified utilizing clustering techniques within the relevant analytic framework.

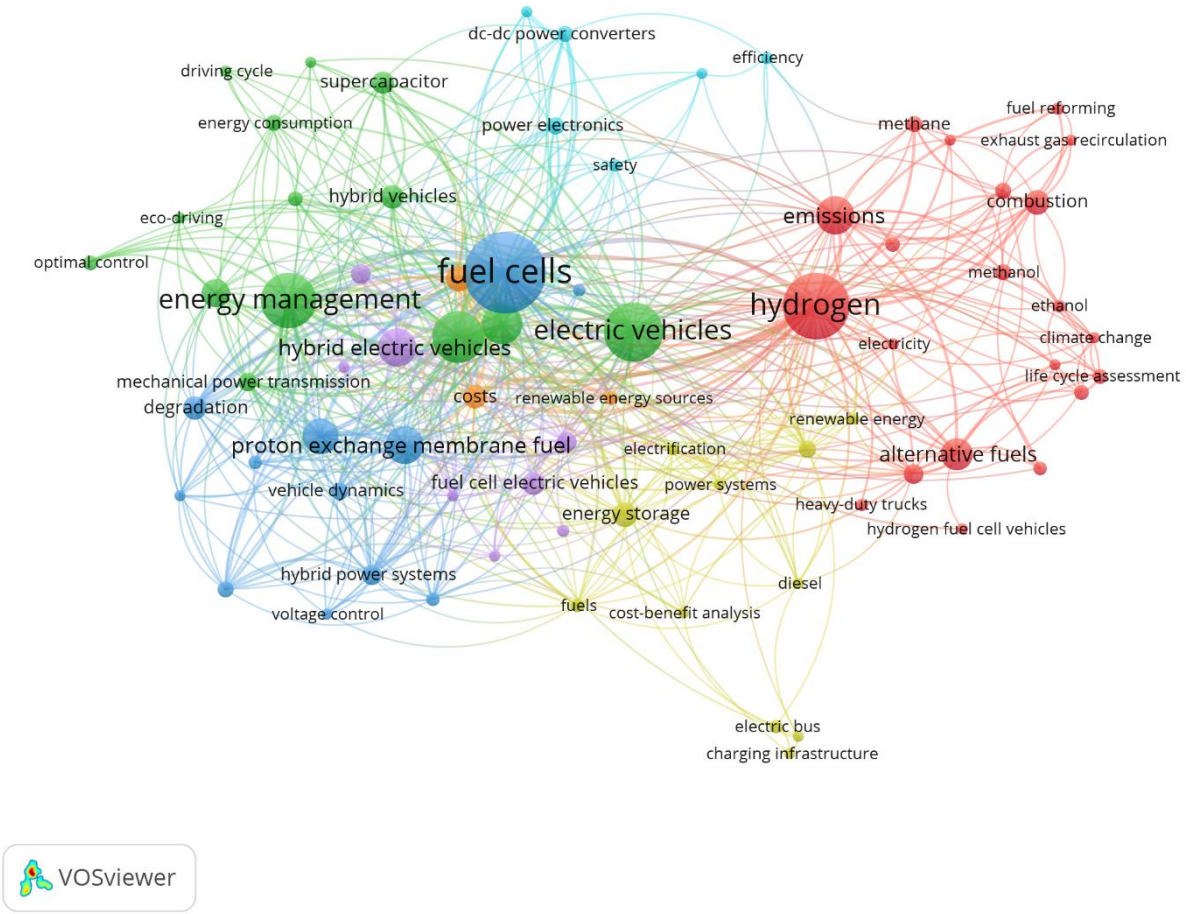


Figure 6. Co-keyword Analysis

The table of key indicators for the associated clusters is provided in Table 6. Columns computation for the table is computed as follows: Keywords: The total number of keywords in that cluster; Total: Occurrences is the sum of the respective scores for all keywords within that given cluster; Average publication year and average citations are the arithmetic mean of the respective scores for all keywords within that given cluster.

Table 6. Key Indicators for the Clusters

Cluster-ID	Total: Keywords	Total: Occurrences	Average: Pub. Year	Average: Citations
1	21	316	2016.97	16.05
2	14	389	2019.00	27.82
3	12	311	2020.58	20.44

Cluster-ID	Total: Keywords	Total: Occurrences	Average: Pub. Year	Average: Citations
4	11	81	2019.11	49.89
5	8	106	2016.75	31.15
6	6	43	2019.01	29.22
7	3	46	2022.21	12.81
Average	**10.71**	**184.57**	**2019.09**	**26.7**

The red color in the aforementioned figure indicates that the initial cluster categorized in VOSviewer is the most numerous of all the clusters defined, as indicated by the number of keywords designated as cluster ID value 1 in the table presented above. It has the second-highest total occurrence value among the clusters. The average publication year for this cluster is the second lowest across all clusters, suggesting that the initial keywords within this cluster were predominantly researched in earlier years compared to the remaining clusters. The average citation score, the second lowest among the other clusters, could indicate that the subjects addressed within this cluster have been widely studied and might be regarded as mature study fields over time. This cluster encompasses a wide array of keywords, including but not limited to those about alternative fuels, innovative fuel types, and sustainability. When the total occurrence values of the keywords in the related cluster are analyzed, Hydrogen has by far the highest value (105). It is prominent that the term remains in the same position in the pertinent cluster compared to other keywords, as indicated by the total link strength value of 220. Upon analyzing the average citation values for the applicable cluster, it is seen that climate change occupies the first position with a value of 42.4.

The cluster highlighted in green in the figure above is the cluster with the second-highest number of second keywords among the words with ID number 2 assigned to the cluster; it has the highest value among the total occurrences value, as well as 285 total links and 862 total link strength. These numbers represent the overall connection and interdependence of subjects within each cluster. Batteries are the cluster's leading keyword, with values of 48 and 226 in both link and total link strength measures, respectively, while electric cars rank second in link value and third in total link strength.

The greatest score of total occurrences indicates significant intellectual engagement in intensive academic research. The cluster's average publication year and citation values are slightly higher than the average for all clusters. Electric vehicles have the highest value of 87 when the total occurrence values of the keywords in the related cluster are analyzed. Analysis of the average citation values for the relevant cluster reveals that energy storage holds the top place with a value of 102.15.

Cluster 3, expressed in blue in the submitted figure, focuses on fuel cells, proton exchange membrane fuels, and energy management systems. This cluster comprises 12 keywords and exhibits a high total link strength of 759 and total occurrences of 311, signifying a well-connected and frequently examined research domain. Cluster 3 has an average publication year of 2020.58, the second-highest value, showing that the research subjects within this cluster represent an emerging and expanding field of research. Cluster 3 has not yet achieved its maximum influence in the

literature, as evidenced by its average citation score of 20.44, significantly lower than the average value of the other clusters. One potential explanation for this value is its relatively recent emergence. The analysis, which was conducted within Cluster 3, confirms that fuel cells have the most occurrences (150), total link strength (332), and links (58), pinpointing it as the most important issue in this cluster. Voltage control is the most recent study topic (2023.00 average publication year); Energy Storage has the greatest citation impact (102.15 average citations).

Cluster 4, which is indicated in yellow in the figure above, is primarily concerned with energy storage. The total number of links in Cluster 4, which includes 11 keywords, is 149. The total link strength is 223, and the occurrence value is 81. These values are significantly lower than the overall cluster averages of 166, 410.57, and 184.57, respectively, suggesting that this cluster is more narrowly focused. The average publication year of 2019.11 is roughly in line with the overall average of 2019.09. The high citation metric indicates that, even though topics in Cluster 4 occur less frequently and are less extensively connected, they are highly influential and impactful in the academic literature, as the average citations of 49.89 far exceed the overall average of 26.77. In this cluster, Energy Storage is consistently the most central and influential topic, as demonstrated by its Links value (26), Total Link Strength (47), Occurrences (20), and Avg. Citations (102.15 score). The most recent research focus is on power systems, with an average publication year of 2023.0.

Cluster 5, shown in purple, has eight keywords. The total number of links is 116, below the average of 166.00. Similarly, total link strength totals 208, compared to the average of 410.57. The total number of occurrences is 106, below the average of 184.57. The mean publishing year is 2016.75, somewhat preceding the average of 2019.09. The average number of citations is 31.15, above the norm of 26.77. The measurements indicate that Cluster 5, possessing fewer keywords and linkages, includes papers with a more significant citation effect, indicating substantial academic importance within a particular research field. In Cluster 5, hybrid electric vehicles have the highest measurements in links (33), total link strength (93), occurrences (42), and average citations (90.62). This signifies that HEVs are pivotal and have a considerable academic impact on the study. In contrast, carbon neutrality, with the latest average publication year (2023.33), has the lowest number of links (3) and total link strength (3), indicating it is a less networked and nascent issue in the discipline. There are six keywords in Cluster 6, which are represented by the color turquoise. The minimum number of links in this cluster is 57, and the overall link strength is 96.

It has the lowest cumulative weight of occurrences (43). The mean publication year is 2019.01, somewhat below the overall mean, but the average citations per keyword is 29.22, marginally over the overall mean. In Cluster 6, dc-dc power converters show the highest values for total link strength (27), and average citations (72.9), while reliability peaks in average publication year (2022.4), and power electronics dominates in occurrences(11).

Cluster 7, colored in amber, has the most outstanding values across three categories: Costs, renewable energy sources, and transportation. Links are directed mainly by transportation (27 links); total link strength is maximized for costs (76); occurrences are most frequent in transportation (21); the average publication year indicates that costs have the most recent publications (2023.3889); the score for average citations is comparatively small, with transportation at the forefront (14.4286). Cluster 7 has significant differences from other clusters, especially with its emphasis on recent publications, with an average publication year of 2022.21, the most current among the clusters. Nonetheless, it has comparatively low values in other measures, such as the number of keywords (3), links (61), total link strength (161), and occurrences (46). These results are markedly inferior to the average values of 10.71, 166.00, 410.57, and 184.57, respectively.

CONCLUSION

This analysis reveals that out of 1858 articles sourced from WOS, the count diminishes to 984 when confined to the transportation science and technology category inside the Web of Science. The papers were viewed and analyzed using the bibliometric visualization program VOSviewer. The analysis results could assist researchers in their research and encourage further research on the topic at hand. Though recent research has provided insights, there is a need for more comprehensive bibliometric analysis to better understand the knowledge structure of this field of study.

The research showed that: 1) research done between 2020 and 2025 make for over half of all research done since 1992; 2) with a substantial 24.16% share of all publications, China is the dominant country;3) USA serves as the principal hub, with the most extensive worldwide linkages within the framework of the co-authorship network map of countries;4) The top research institute is DOE;5) IEEE is the leading publisher in terms of publishing volume;6) The paper written by Khaligh and Li (2010) has the highest number of citations;7) The articles written by Khaligh and Li, 2010 and Emadi et al., 2005 are among the research papers with the highest co-citation number;8) The keyword with the highest number of occurrences and total link strength is Fuel Cells;9) Seven clusters were identified utilising the keyword co-occurrence analysis results.

When the co-occurrence keywords reported in Kabakuş's [2024] research, "Bibliometric Analysis and Research Trend of Sustainable Green Transportation," are compared to the current research findings, the word emission is shown to be one of the frequent keywords in both studies. It is worth noting that the term Life cycle assessment appears within clusters containing the keyword "emission" in both of these studies[Kabakuş, 2024]. This body of evidence clearly shows a link between emissions and life cycle assessment in both research topics.

When the number of country-specific publications in the study titled 'Transport sustainability - a bibliometric, systematic methodological review and future research opportunities', written by Tetteh et al. (2024), is compared to the current research findings, it becomes apparent that China is the clear leader in the field in both bibliometric analyses[Tetteh et al., 2024].

The study findings provided an instant representation of the current status and essence of hydrogen and fuel cells within transportation science and technology studies, facilitating the direct tracing of the subject's origins.

The results of this study have aided in offering a thorough summary of important publications to identify exciting possibilities for future research, illustrating the trajectory and research hubs of fuel cells and hydrogen in the domains of transportation science and technology.

In the literature review, no studies were found in English or Turkish for a bibliometric analysis on Hydrogen and Fuel Cells in Transportation Science and Technology Studies. In this context, the study conducted within the framework of our research is significant because it is one of the first studies in the field. Hydrogen and fuel cell technologies are essential advancements within the field of Transportation Science and Technology aimed at supporting sustainable transportation systems. One of the most important things about this study is that it systematically reviews scientific progress in the subject and gives policymakers, business leaders, and academics strategic insights. Another important element of the research is to determine which topics the research focuses on over time, which countries and institutions stand out in research when compared to others, and to identify trends in the scientific literature. The next significance of the publication is to provide policymakers and industry experts with solid, large-scale analytical data that they can use for developing energy alternatives for transportation. Another important element that differentiates the present study from other studies is how it deploys scientific mapping methods to systematically analyze literature networks and clusters. The new vision offered by the research includes a contribution to the systematic identification of research gaps as well as a clear indication of which parts of new technological applications have not been fully analyzed.

The paper presents key elements and research trends important to the developmental dynamics of hydrogen and fuel cell technologies within transportation. Regular bibliometric analyses on this topic will systematically identify gaps in the field and contribute to the development of future national and international strategies based on evidence.

In addition to illustrating that hydrogen and fuel cell technologies are a rapidly evolving strategic area in transportation research, this study also provided a comprehensive overview of current scientific trends. The research indicates that hydrogen and fuel cells are an emerging field of study when assessed within the context of transportation science and technology. The literature trends indicate that hydrogen technologies are significantly associated with emissions, which suggests that there are substantial opportunities for environmental policies.

Limitations of the Study:

The bibliographic technique refines article statistics while supporting researchers in generalizing research contents and relevance, as shown by visualization maps. However, even the most extensive analytical methods have limits in some situations. Initially, the database was chosen from the WOS Core Collection, excluding additional sources like Scopus and Google Scholar.

Future Research:
Future literature collection and organization using WOS and other databases may enhance understanding of research status and development trends.

Compliance with Ethical Standards

Conflict of Interest Declaration: *The author declare that there are no conflicts of interest between themselves and/or any third parties or institutions regarding this work.*

Ethics Committee Approval: Ethics committee approval is not required for this study.

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