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Review Paper

Trends, Advances, and Future Directions in Fuel Cell Electric Vehicle Performance: A Bibliometric Analysis Using the PAGER Framework

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Abstract

The global shift toward sustainable transportation has positioned fuel cell electric vehicles (FCEVs) as a key zero-emission mobility solution. Despite notable technological progress, FCEV adoption faces persistent barriers including high hydrogen production costs, limited infrastructure, and lack of real-world validation. This study employs the Pattern, Advance, Gap, Evidence for Practice, and Research Recommendation (PAGER) framework to conduct a comprehensive bibliometric analysis of 200 peer-reviewed publications from 2005 to 2024, focusing on performance trends, technological advancements, research gaps, practical applications, and future research directions. The analysis uses Scopus data and VOSviewer for visualization and thematic mapping to identify three distinct research phases: early exploration, gradual refinement, and rapid technological maturity. Key findings highlight advancements in energy management strategies, hybrid powertrain integration, and hydrogen storage optimization. However, critical gaps remain in economic modeling, behavioral adoption analysis, and infrastructure scalability. This study offers a structured roadmap for future research and practice, emphasizing the need for dynamic total cost of ownership models, interdisciplinary policy interventions, and real-world pilot projects. The findings serve as a strategic reference for academics, industry stakeholders, and policymakers to accelerate the global transition to sustainable FCEV-based transportation systems.

Keywords: Bibliometric analysis; Decarbonization transportation; Energy management strategies; Fuel cell electric vehicles; PAGER framework

1. Introduction

The transportation sector is a significant contributor to global greenhouse gas (GHG) emissions [1], [2], accounting for approximately 20–22.3% of energy-related CO_2 emissions [3], [4]. Electric vehicles (EVs), particularly fuel cell electric vehicles (FCEVs), offer a viable pathway toward decarbonizing transportation by utilizing hydrogen as a clean energy carrier [5], [6], [7]. With high efficiency, extended driving range, and fast refueling capabilities [8], FCEVs are well-suited for a wide range of applications, from passenger vehicles to heavy-duty transport. However, despite these advantages, FCEV adoption remains limited due to challenges such as hydrogen storage constraints [9], high production costs [10], inadequate infrastructure [11], [12], and public perception and safety concerns [9], [12], [13]. Consequently, research on improving FCEV performance has gained momentum, with a focus on key areas such as hydrogen storage [14], fuel cell durability [15], [16], energy efficiency [17], [18], economic feasibility, and efforts to reduce hydrogen production costs by exploring renewable energy-based production pathways such as solar or wind-supported electrolysis, or biomass gasification [19]. A bibliometric approach can provide valuable insights into this evolving research landscape by identifying patterns, technological advancements, and emerging research gaps [20], [21].

Over the past five years, bibliometric studies on EVs, hybrid electric vehicles (HEVs), and FCEVs have rapidly expanded, offering insights into energy management strategies, life cycle cost (LCC) analysis, and various technological, socio-economic, and innovation trends. For instance, Raboaca et al. [22] examined optimal energy management strategies for EVs and FCEVs through a bibliometric analysis using Web of Science (WoS) and VOSviewer, identifying 127 strategies categorized by algorithm type (rule-based, optimization, machine learning) and primary objectives (energy efficiency, fuel savings, hydrogen consumption reduction). Their study highlighted key advancements such as particle swarm optimization, fuzzy control systems, and reinforcement learning but lacked an exploration of cross-disciplinary collaboration. Meanwhile, Ayodele and Mustapa [23] conducted a bibliometric review of LCC analysis for EVs, evaluating their economic competitiveness and sustainability relative to internal combustion engine vehicles (ICEVs). Their findings underscored that LCC varies significantly depending on government policies and economic conditions, with battery costs emerging as a major challenge, and emphasized the absence of a globally standardized methodology for comparative studies.

Bibliometric studies focused specifically on FCEVs offer broader technological and geographical perspectives. Alvarez-Meaza et al. [24] mapped scientific and technological knowledge related to FCEVs by analyzing patents and publications from Scopus and Lens between 1999 and 2019. Their study identified dominant contributors, including the United States (US), China, and Japan, with key themes such as hydrogen production and storage, energy management systems, and greenhouse gas reduction. Leading automakers such as Toyota, Honda, and Hyundai played a crucial role in advancing FCEV technology through significant patent activity. Similarly, Agyekum et al. [25] conducted a bibliometric analysis of hydrogen FCEVs, utilizing Scopus data and visualization tools such as VOSviewer and Biblioshiny to explore research trends, technological evolution, and prospects. Their study identified 3,107 documents, primarily from China, the US, and Japan, emphasizing advancements in thermal management, machine learning-based energy optimization, and hybrid vehicle design.

From a broader perspective, Pinto et al. [26] examined the growth of technical, socio-economic, and innovation-related EV research through a bibliometric analysis of 10,426 publications from WoS between 1989 and 2020. Their findings highlighted key themes such as charging infrastructure, vehicle-to-grid (V2G) systems, energy management, and consumer adoption, with the US and China leading in publication volume. However, their study also revealed a significant market adoption gap, particularly compared to European countries like Norway. At the regional level, Setiyo et al. [27] analyzed EV research and development trends in Indonesia, Malaysia, and Thailand using Scopus data from 2015–2025. Their findings indicated Malaysia’s leadership in research contributions, Thailand’s progress in EV adoption driven by strong government policies and infrastructure investments, and Indonesia’s untapped potential due to its abundant nickel reserves. However, challenges such as limited charging infrastructure, high costs, and reliance on coal-based electricity remain major barriers in these countries.

Although these studies provide valuable insights into EV, HEV, and FCEV adoption from various perspectives, they lack a comprehensive analysis of FCEV performance. Additionally, most existing bibliometric studies have not fully explored advanced bibliometric techniques and primarily rely on descriptive publication trend analyses without establishing clear correlations or causal relationships between research trends and practical applications. Another critical limitation is the absence of an integrated methodology, such as the Pattern, Advance, Gap, Evidence for Practice, Research Recommendation (PAGER) framework [21], which systematically links observed patterns and technological advancements with actionable recommendations.

To address these limitations, this study aims to provide a structured and unique bibliometric analysis of FCEV performance based on the PAGER framework, utilizing VOSviewer for visualization to offer deeper and more comprehensive insights for policymakers, industry stakeholders, and researchers. The study is guided by the following key research questions: (1) What are the major trends in FCEV performance research? (2) What technological advancements have significantly shaped this field? (3) What critical gaps remain unaddressed? and (4) How can existing evidence inform practical applications and guide future research? By leveraging Scopus as the sole database [21], [28], [29], this study ensures a robust and reproducible dataset, laying the groundwork for future innovations in FCEV technology.

2. Methodology

2.1. Study Design and Theoretical Framework

Bibliometric analysis serves as a systematic and essential method for mapping the evolution of scientific knowledge. By leveraging advancements in citation metrics, textual data analysis, and publication trends, this approach enables the effective management and organization of extensive datasets while identifying emerging research directions [30]. Its structured and reproducible nature makes bibliometric analysis a valuable tool for conducting systematic literature reviews [20].

In this study, we adopt the PAGER framework, developed by Bradbury-Jones et al. [31] and utilized by Apriandi et al. [21], with modifications tailored to align with the specific objectives of this research. The PAGER framework enhances bibliometric analysis by offering a structured, theory-informed lens for interpreting large-scale publication data. It systematically identifies thematic patterns and clusters (Pattern), highlights technological and methodological breakthroughs (Advance), pinpoints underexplored or neglected areas (Gap), assesses real-world applicability and policy relevance of research findings (Evidence for Practice) and outlines actionable future research directions (Research Recommendation) [21]. This integrated approach transforms bibliometric studies from purely descriptive mappings into strategic analyses, enabling researchers to understand not only what has been studied but also what matters, what is missing, and where future efforts should be directed. By bridging the gap between quantitative bibliometric metrics and qualitative insight, PAGER ensures findings are more meaningful, impactful, and aligned with both academic and practical needs. By applying this structured approach, this study aims to provide a comprehensive and systematic bibliometric evaluation of FCEV research, offering valuable insights for policymakers, industry stakeholders, and researchers.

2.2. Data Collection Process

The data collection process for this bibliometric analysis follows a systematic and well-defined methodology, as outlined in **Table 1**. The Scopus database (Elsevier) was selected as the primary data source due to its comprehensive documentation and extensive repository of scholarly articles [32], [33], [34], including those relevant to FCEV research. Data extraction was conducted via the Scopus platform on January 18, 2025, starting at 21:30 local time (Waktu Indonesia Barat/WIB = GMT +7).

Table 1. Review protocol used in data search

Subject	Description
Database	Scopus (Elsevier)
Keywords	Fuel cell electric vehicle performance
Search field	Title, abstract, keywords
Time interval	2005-2024
Subject area	Engineering
Publication type	Research articles
Publication language	English
Source type	Journal
Pubstage	Final

To align with the study's objectives of investigating research trends, technological advancements, and future research potential in this specialized field, an initial search was performed using the keyword string: "fuel cell electric vehicle performance". This query retrieved a total of 4,170 documents. A subsequent filtering process, incorporating inclusion and exclusion criteria, was applied using the final refined search query: TITLE-ABS-KEY (fuel AND cell AND electric AND vehicle AND performance) AND PUBYEAR > 2004 AND PUBYEAR < 2025 AND (LIMIT-TO (EXACTKEYWORD, 'Fuel Cell Electric Vehicle') OR LIMIT-TO (EXACTKEYWORD, 'Fuel Cell Hybrid Electric Vehicles') OR LIMIT-TO (EXACTKEYWORD, 'Fuel Cell Hybrid Electric Vehicle')) AND (LIMIT-TO (SUBJAREA, 'ENGI')) AND (LIMIT-TO (DOCTYPE, 'ar')) AND (LIMIT-TO (LANGUAGE, 'English)) AND (LIMIT-TO (SRCTYPE, 'j')) AND (LIMIT-TO (PUBSTAGE, 'final')). This query refinement resulted in a curated dataset of 200 high-relevance journal articles for quantitative bibliometric analysis.

To complement the quantitative analysis, a qualitative screening process was conducted by reviewing the titles, abstracts, and, where necessary, the full texts of the retrieved documents to ensure their alignment with the study's research objectives. This rigorous filtering approach enabled the identification of a refined subset of studies that formed the basis for in-depth analysis using the PAGER framework. Only articles that directly contributed to the understanding of FCEV performance and technological innovation were included. By applying strict inclusion and exclusion criteria (selecting only peer-reviewed journal articles published in their final form, written in English, and indexed under relevant engineering subject areas), this methodological process enhances the robustness, transparency, and reproducibility of the bibliometric analysis.

2.3. Bibliometric Mapping and Analytical Approach

This study employs VOSviewer to explore the research landscape related to FCEV performance through author keyword analysis, bibliographic coupling, and citation network mapping. By integrating the PAGER framework, this approach enables the development of a comprehensive bibliometric map that identifies key trends, patterns, and research relationships, while also uncovering existing gaps and providing recommendations for future research directions.

Through the systematic mapping of major contributions in the field, this method offers valuable insights into the evolution and dynamics of FCEV research, highlighting technological advancements and emerging research trajectories. Moreover, it provides a holistic perspective on the progress achieved, ensuring a structured and data-driven foundation for guiding future studies and innovation in FCEV technologies.

3. Results and Discussion

3.1. Pattern: Publication Trends in Fuel Cell Electric Vehicle Performance Research

3.1.1. Publication Trends by Year

Figure 1 illustrates the publication trends related to FCEV performance research over the past 20 years, encompassing a total of 200 documents. The research evolution is categorized into three distinct phases: Phase I, representing the early exploration stage; Phase II, indicating a period of steady growth and technological refinement; and Phase III, reflecting a phase of rapid expansion and technological maturity. This classification highlights the progression of FCEV research, from initial conceptual studies to broader technological adoption and real-world applications.

3.1.1.1. Phase I (2005–2008): Early Exploration

This phase marks the initial stage of FCEV research, characterized by a low volume of publications and a focus on exploratory studies. Researchers sought to establish fundamental concepts and assess the feasibility of integrating fuel cell systems into electric vehicles. Park et al. [35] pioneered this effort by investigating operational algorithms for HEVs that combined fuel cells with auxiliary power sources. Their study underscored the importance of optimizing energy management strategies (EMS) to enhance system performance. Meanwhile, Marco & Vaughan [36] developed a control-based model for designing and simulating hybrid electric powertrains, emphasizing the integration of fuel cells as the primary energy source. These studies

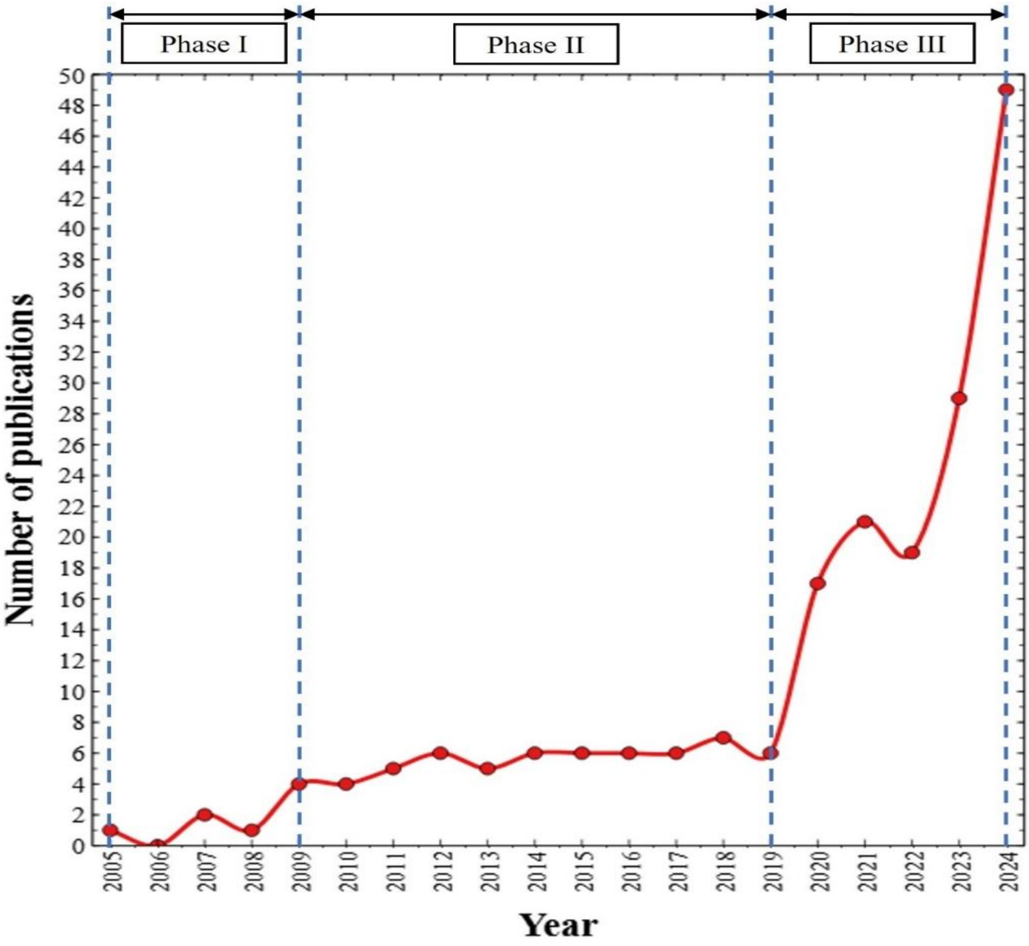

Figure 1. Distribution of publication by year. n = 200 documents

provided crucial early insights into how fuel cell systems could be incorporated into hybrid vehicle architectures to improve energy efficiency and reduce emissions.

However, research during this phase faced significant challenges. The absence of adequate hydrogen infrastructure, high costs, and the immaturity of fuel cell technology posed major barriers to practical FCEV implementation. Most studies were limited to laboratory or simulation-based environments, with minimal real-world validation. While publications in this period highlighted the transformative potential of FCEVs in addressing global energy and environmental challenges, they offered few actionable solutions for commercialization or large-scale deployment. The low number of publications during this period also reflected the early-stage competition between fuel cells and other emerging alternative energy solutions. Nevertheless, the exploratory research in Phase I was instrumental in identifying fundamental challenges, such as fuel cell durability, energy management, and system integration, forming the foundation for the gradual growth and technological refinement observed in later phases.

3.1.1.2. Phase II (2009–2019): Gradual Growth and Technological Refinement

This phase saw a steady increase in publications, reflecting the growing research interest in improving FCEV technology. Research efforts during this period focused on overcoming technical limitations and addressing practical challenges related to scaling up FCEVs for broader adoption. For example, Ommi et al. [37] explored advancements in FCEV drive cycles and energy efficiency, providing insights into vehicle performance optimization through model evaluations. These studies emphasized the importance of improving energy consumption metrics and developing more efficient operational strategies, thereby enhancing FCEV competitiveness against internal combustion engine (ICE) vehicles. Additionally, many studies highlighted hydrogen infrastructure development as a key enabler for supporting FCEV expansion on a larger scale.

During this period, researchers also emphasized policy-driven approaches, as governments worldwide introduced incentives and environmental regulations to accelerate FCEV commercialization. Several publications examined economic strategies to reduce production costs, while others analyzed government-led pilot projects designed to demonstrate the feasibility of FCEVs in public transportation systems. Despite incremental technological advancements, the moderate growth in publications suggests that challenges such as high costs, inadequate infrastructure, and technical barriers (including fuel cell durability) persisted. Researchers began shifting their focus toward real-world applications, yet large-scale implementation of FCEVs remained limited. Research findings from Phase II played a crucial role in bridging fundamental research from Phase I with the rapid technological expansion of Phase III, laying the groundwork for overcoming key commercialization barriers.

3.1.1.3. Phase III (2020–2024): Rapid Expansion and Technological Maturity

This phase marks an exponential surge in research output, reflecting FCEV research transitioning toward technological maturity and broader adoption. This rapid growth has been driven by key technological breakthroughs, including fuel cell design improvements that enhance durability and cost efficiency (critical factors in reducing production costs and improving FCEV market competitiveness). Additionally, significant advancements in system integration have enabled more efficient fuel cell operations within complex vehicle architectures. Research during this phase highlights the practical benefits of FCEVs, such as high energy efficiency, emission reductions, and long driving ranges, which have been reinforced through lifecycle assessments and large-scale field trials. These studies indicate a shift from theoretical models to real-world applications, focusing on overcoming deployment challenges, including hydrogen infrastructure development and public acceptance.

Beyond technological advancements, the global push for decarbonization, driven by agreements like the Paris Agreement, alongside substantial government and industry investments, has fueled the expansion of FCEV research. This support has accelerated collaborations between academia and industry, leading to practical, scalable innovations for FCEV deployment. Large-scale pilot projects integrating FCEVs into public transportation systems serve as tangible proof of this collaboration, demonstrating a commitment to reducing dependence on fossil fuels. The increasing number of joint publications during this phase strongly emphasises practical solutions for large-scale adoption, including cost-effectiveness and infrastructure sustainability.

By leveraging technological breakthroughs, policy incentives, and renewable energy integration, researchers have positioned FCEVs as a critical component of the low-carbon transportation transition. This phase not only consolidates the foundational work from previous research periods but also sets the stage for future innovations and mass adoption, paving the way for next-generation advancements in fuel cell electric mobility.

3.1.2. Keywords Analysis

The visualized network map generated by VOSviewer (**Figure 2**) reveals the interconnected and multidisciplinary nature of FCEV research, with "fuel cell electric vehicle" positioned as a central node linking key research domains such as energy management, hydrogen infrastructure, and battery integration. Strong inter-cluster connections, particularly between keywords such as "energy management strategy" and "fuel cell hybrid electric vehicle", emphasize their shared relevance in addressing system-level challenges. The network also highlights a significant focus on sustainability, as indicated by the connections between "renewable energy," "hydrogen," and "fuel cell", reflecting the growing emphasis on decarbonization and sustainable fuel production driven by global policy initiatives. Additionally, the presence of advanced computational approaches, such as "particle swarm optimization" and "deep reinforcement learning", signals the increasing adoption of cutting-edge techniques to solve complex energy management and optimization challenges in FCEVs.

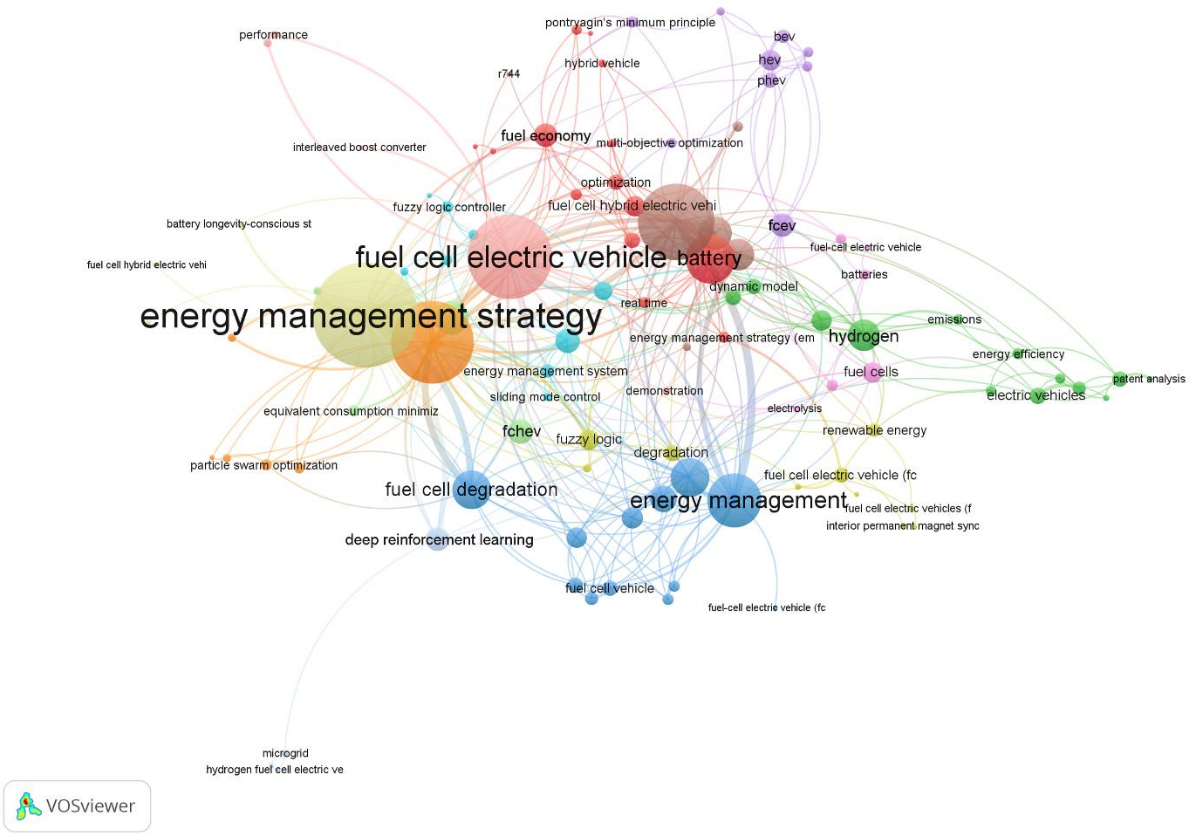

Figure 2. The trend of fuel cell electric vehicle (FCEV) performance based on author keywords over the period 2005 – 2024

Table 2. Top five author keywords based on total link strength

Keywords	Cluster	Total Link Strength	Occurrence
Energy management strategy	13	76	34
Fuel cell hybrid electric vehicle	7	57	25
Fuel cell	8	52	24
Energy management	3	35	15
Battery	1	31	9

Based on the data in **Table 2**, this analysis delves into the trends, interconnections, and key studies associated with the top five author keywords, providing a deeper understanding of the evolving FCEV research landscape.

"Energy management strategy" (total link strength (TLS): 76; occurrence: 34) emerges as the most influential keyword, underscoring its crucial role in optimizing power distribution across fuel cells, batteries, and auxiliary systems in hybrid powertrains. Advanced algorithmic systems have been extensively explored to enhance real-time energy efficiency, as demonstrated by Park et al. [35]. Similarly, Marco & Vaughan [36] highlighted the importance of control-oriented designs for hybrid powertrain optimization. Recent advancements integrate intelligent systems, including machine learning and reinforcement learning, to dynamically adjust energy management strategies based on varying driving conditions, addressing key challenges such as fuel cell degradation. The strong network connection between this keyword and "fuel cell degradation" further emphasizes its role in extending component lifespan and ensuring reliability in hybrid configurations.

"Fuel cell hybrid electric vehicle" (TLS: 57; occurrence: 25) reflects research on hybrid designs that integrate fuel cells with energy storage systems, such as batteries and supercapacitors. These configurations leverage the fast response time of batteries and the long-range capability of fuel cells, enhancing efficiency and reducing hydrogen consumption, as demonstrated by Zhao et al. [38] and Ommi et al. [37]. The strong clustering of this keyword with "energy management strategy" and "battery" underscores its critical role in hybrid system optimization, particularly in multi-source energy management systems designed to balance power flow and mitigate limitations such as fuel cell startup delays. Concurrently, "fuel cell" (TLS: 52; occurrence: 24) represents fundamental research, primarily focusing on proton exchange membrane fuel cells (PEMFCs) due to their high power density and automotive suitability. Additionally, critical challenges related to fuel cell durability and cost reduction have been widely explored, while its connection with "hydrogen" and "renewable energy" highlights the alignment of FCEV research with sustainability objectives, particularly the production of green hydrogen from renewable sources such as solar and wind energy.

"Energy management" (TLS: 35; occurrence: 15) and "battery" (TLS: 31; occurrence: 9) further reflect energy system integration in FCEVs. Energy management encompasses hybrid energy systems, intelligent control mechanisms, and vehicle-to-grid (V2G) capabilities, positioning FCEVs as active components in future smart grid ecosystems. Marco et al. [36] and similar studies emphasize the necessity of robust energy management systems to maintain operational stability under dynamic power demands. Meanwhile, batteries play a pivotal role in load balancing, regenerative braking, and peak power support in hybrid configurations. Zhao et al. [38] highlight the importance of thermal management and longevity-conscious strategies to address challenges such as overheating and degradation. Advances in battery materials and management systems have led to higher energy densities and faster charging capabilities, catering to consumer demands while enhancing system efficiency.

These interconnected research themes underscore the importance of seamless technology integration, sustainability-focused innovations, and advanced computational techniques such as particle swarm optimization and deep reinforcement learning to tackle complex challenges and position FCEVs as key players in the future energy ecosystem.

3.1.3. *Global Research Landscape in Fuel Cell Electric Vehicle: Top Five Contributing Countries*

The bibliometric analysis of the top five countries in FCEV research (China, Canada, France, the United Kingdom, and the United States (**Table 3**) reveals key insights into global trends and collaborations.

China leads the field, boasting the highest total link strength (TLS: 3570), the largest number of publications (68), and an outstanding normalized citation impact (80.39). These metrics highlight China’s central role in advancing EMS, fuel cell optimization, and green hydrogen production. Strong international collaborations with countries like the United States, Canada, and France reflect China’s strategic investments in renewable energy technologies and hydrogen infrastructure, positioning FCEVs as a cornerstone of sustainable transportation. The high citation impact of Chinese research further underscores its relevance in global decarbonization efforts and the transition to clean energy solutions.

Canada (TLS: 1652, 17 publications) and France (TLS: 1446, 15 publications) serve as key innovation hubs, focusing on sustainability-driven advancements such as hydrogen storage systems and renewable energy integration. Canadian researchers emphasize lifecycle assessments and environmentally friendly approaches, while French research excels in hybrid energy systems and hydrogen electrolysis, laying the foundation for highly efficient FCEV architectures. Meanwhile, the United Kingdom (TLS: 1162, 15 publications) and the United States (TLS: 1133, 21 publications) play critical roles in

Table 3. Top five contributing countries based on total link strength

Country	Cluster	Total Link Strength	Number of Publications	Citations	Norm. Citation
China	3	3570	68	1866	80.39
Canada	2	1652	17	698	15.59
France	2	1446	15	601	12.71
United Kingdom	1	1162	15	243	18.75
United States	1	1133	21	969	20.20

policy-driven innovation and practical implementation. The UK translates cutting-edge research into actionable strategies for hydrogen adoption, while the US leads advancements in vehicle-to-grid (V2G) integration and hydrogen infrastructure development.

Collectively, these five nations demonstrate strong collaboration and unique contributions, driving the development of key technologies such as advanced fuel cell control algorithms, modular hydrogen storage systems, and integrated vehicle-to-grid (V2G) architecture, while aligning FCEV research with global sustainability goals. The synergy between research and policy frameworks underscores the importance of international cooperation in scaling up FCEV adoption as a key solution for sustainable transportation.

3.1.4. Institutional Contributions to Fuel Cell Electric Vehicle Research

The network visualization highlights leading institutions contributing to FCEV research (**Figure 3**), underscoring their pivotal role in shaping global advancements in this field. "The School of Automotive Studies" emerges as a central hub, reflecting extensive collaborations and its influence in key research areas, including energy management, fuel cell optimization, and hydrogen infrastructure development. Institutions such as "Nanjing University of Aeronautics and Astronautics" and the "National Engineering Laboratory" demonstrate significant contributions, particularly in engineering innovations and system integration, emphasizing their technical expertise and leadership in advancing FCEV technology. Other major contributors, such as the "Delft Center for Systems and Control" and "Quantis, Zurich", highlight the interdisciplinary nature of FCEV research, integrating lifecycle assessment methodologies and renewable energy optimization into the field.

The clustering of institutions within the network visualization reveals strong international collaborations, fostering knowledge exchange and driving innovation. The interconnected network between academic institutions and industry players reflects global efforts to position FCEVs as a sustainable solution in the transition toward a low-carbon transportation system.

3.1.5. Key Contributors to Fuel Cell Electric Vehicle Research

The analysis of the top five authors based on TLS provides valuable insights into the key contributors driving FCEV research. **Figure 4** presents a network visualization of influential authors in FCEV research, while **Table 4** summarizes the top five authors ranked by TLS.

"Kandidayeni, M." emerges as the most influential author, leading with a TLS of 27, eight publications, and 308 citations, reflecting the strong impact and extensive collaborative reach of

Figure 3. Visualization of the network of leading FCEV research institutions over the period 2005 – 2024

Table 4. Top five authors based on total link strength

Authors	Cluster	Total Link Strength	Number of Publications	Citations	Norm. Citation
Kandidayeni, M.	2	27	8	308	8.66
Boulon, L.	2	24	7	265	7.38
Chaoui, H.	5	13	4	262	6.19
Trovao, J.P.F.	2	10	3	30	1.57
Ravey, A.	1	8	2	296	3.87

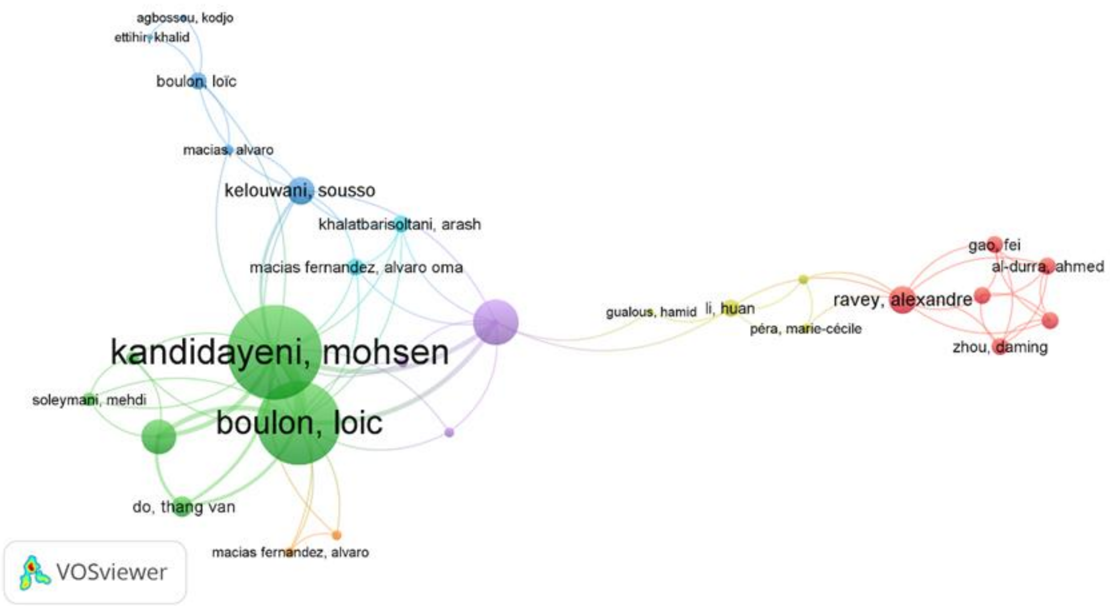

Figure 4. Visualization of the network of leading FCEV research authors based on total link strength over the period 2005 - 2024

their work within the research community. Kandidayeni's research focuses on energy management strategies and hybrid vehicle systems [39] has significantly contributed to optimizing FCEV technologies, particularly in enhancing powertrain efficiency and fuel cell durability. Following closely, "Boulon, L." ranks second with a TLS of 24, seven publications, and 265 citations, emphasizing their collaborative efforts in advancing energy storage integration and improving fuel cell efficiency. Their active partnership with Kandidayeni is evident within the same network cluster, further reinforcing the importance of their collective contributions to the field.

Additionally, "Chaoui, H." demonstrates substantial influence, with a TLS of 13, four publications, and 262 citations, focusing on control systems and powertrain design for HEVs. Chaoui's interdisciplinary approach bridges the gap between theoretical advancements and practical applications in FCEV research, playing a critical role in enhancing system stability and performance. Meanwhile, "Joao P.F. Trovao", with a TLS of 10, three publications, and 30 citations, contributes to energy storage solutions and power management, complementing the broader efforts of Kandidayeni and Boulon in developing hybrid energy storage frameworks for FCEVs. Lastly, "Ravey, A.", with a TLS of 8 and 296 citations from two publications, has made a significant impact, particularly in control strategies for energy management in HFCEVs [40].

This diverse yet interconnected group of researchers highlights the importance of collaboration and interdisciplinary approaches in addressing the challenges of FCEV adoption, bridging the gap between theoretical innovations and practical applications to drive the widespread development and deployment of FCEVs.

3.1.6. *Most Cited Research Papers*

Table 5 highlights key publications that have significantly shaped FCEV performance research over the past two decades. One of the most influential contributions is the study by Hegazy, O., titled "Analysis, Modeling, and Implementation of a Multidevice Interleaved DC/DC Converter for Fuel Cell Hybrid Electric Vehicles" [41]. This paper introduces an innovative multidevice interleaved boost DC/DC converter (MDIBC) for fuel cell hybrid electric vehicles (FCHEVs). The converter is designed to minimize input current ripple, reduce output voltage fluctuations, and decrease the size of passive components while achieving high efficiency and reduced electromagnetic interference (EMI). By utilizing a small-signal model for dynamic performance analysis and a DSP-based dual-loop digital control system, MDIBC demonstrates superior efficiency, transient response, and component size reduction compared to conventional converter topologies.

However, the study has limitations in scalability to higher power levels, adaptability to diverse load profiles, and economic feasibility assessments for commercial implementation.

In the environmental domain, Bauer, C. in "The Environmental Performance of Current and Future Passenger Vehicles: Life Cycle Assessment Based on a Novel Scenario Analysis Framework" [42] evaluates the environmental impact of different vehicle technologies, including internal combustion engine vehicles (ICEVs), HEVs, battery electric vehicles (BEVs), and FCEVs, through a life cycle assessment (LCA) up to 2030. The study finds that BEVs and FCVs can reduce greenhouse gas (GHG) emissions by up to 80% compared to ICEVs, provided that non-fossil electricity and hydrogen sources are used. However, the study also identifies higher environmental burdens for BEVs and FCEVs in categories such as human toxicity and fine particulate matter formation, primarily due to battery and fuel cell production processes. Critical gaps include limited evaluations of large-scale adoption impacts, grid strain, material scarcity for battery production, and a lack of policy discussions on hydrogen infrastructure development.

Schaltz et al. in "Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle" [43] investigate the impact of battery and ultracapacitor sizing on FCHEV performance and battery lifespan. Their study demonstrates that combining high-energy-density batteries with high-power-density ultracapacitors results in an efficient and lightweight system. The proposed energy management strategy (using the ultracapacitor as a high-pass filter for peak loads or as an energy buffer to reduce battery depth of discharge) proves effective in extending battery lifespan. However, the study does not explore scalability for real-world applications, long-term cost implications, or the impact of varying driving cycles and environmental conditions.

Meanwhile, Ettihir et al. in "Optimization-Based Energy Management Strategy for a Fuel Cell/Battery Hybrid Power System" [44] introduce an adaptive EMS based on Pontryagin's minimum principle (PMP), enhanced with an adaptive recursive least square (ARLS) algorithm to optimize power distribution in FCHEVs while minimizing hydrogen consumption. This EMS approach accounts for fuel cell degradation and operational conditions such as temperature and pressure, leading to improved efficiency and system reliability, as confirmed through experimental validation on both healthy and degraded PEMFCs. However, scalability to more complex hybrid systems and life cycle analysis for real-world driving conditions remain underexplored and require further research.

Table 5. The top five most-cited documents

First Author	Year	Document Title	Journal	Citations	Ref.
Hegazy, O.	2012	Analysis, Modeling, and Implementation of a Multidevice Interleaved DC/DC Converter for Fuel Cell Hybrid Electric Vehicles.	IEEE Transactions on Power Electronics	360	[41]
Bauer, C.	2015	The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework.	Applied Energy	351	[42]
Schaltz, E.	2009	Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle.	IEEE Transactions on Vehicular Technology	351	[43]
Ettihir, K.	2016	Optimization-based energy management strategy for a fuel cell/battery hybrid power system.	Applied Energy	231	[44]
Robledo, C.B.	2018	Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building.	Applied Energy	220	[45]

Lastly, Robledo et al. in "Integrating a Hydrogen Fuel Cell Electric Vehicle with Vehicle-to-Grid Technology, Photovoltaic Power, and a Residential Building" [45] explore the integration of FCEVs into a microgrid comprising residential buildings and photovoltaic (PV) power. Conducted as part of a Dutch pilot project, the study demonstrates that FCEVs operating in vehicle-to-grid (V2G) mode can supply up to 10 kW of power, reducing imported electricity demand by approximately 71%. Simulations of a microgrid with 10 homes and 5 FCEVs highlight significant economic potential, particularly if hydrogen prices drop below €8.24/kg. However, further research is needed to evaluate seasonal performance variations, scalability to diverse microgrid configurations, and long-term impacts of hydrogen infrastructure deployment. Future studies should focus on optimizing V2G strategies, improving hydrogen storage solutions, and assessing life-cycle impacts to enhance the sustainability and economic viability of hydrogen-based energy systems.

These influential publications illustrate the technological, environmental, and economic dimensions of FCEV advancements, highlighting both opportunities and existing challenges. Future research should emphasize scalability, real-world applicability, and policy frameworks to accelerate FCEV adoption as a critical component of the low-carbon transportation ecosystem.

3.2. Advance: Technological and Scientific Progress

3.2.1. Advancements in Fuel Cell Electric Vehicle Design Optimization and Operational Parameters

Research on FCEVs has progressed significantly, with a focus on design optimization and operational parameter improvements to enhance system performance. Farhani et al. [46] investigated a three-phase interleaved boost DC/DC converter, designed to minimize input current ripple, reduce voltage stress, and improve reliability for FCEV applications. Experimental validation using a DSP- and FPGA-based prototype demonstrated high efficiency and automotive compatibility. However, further studies are required to assess long-term reliability under diverse environmental conditions and scalability to meet higher power demands. Similarly, Kang et al. [47] proposed an optimization algorithm for interior permanent magnet synchronous motor (IPMSM) design, achieving higher torque density, reduced cogging torque, and lower material costs. While this algorithm outperforms conventional methods, its real-world applicability under varying load and temperature conditions remains unexplored.

Innovations in thermal management and hydrogen storage systems have also advanced FCEV technology. Nguyen et al. [48] developed a cryogenic hydrogen storage tank using porous materials, significantly reducing system weight and cost. However, the long-term stability of the adsorptive materials under repeated cryogenic cycles and varying environmental conditions requires further investigation. Meanwhile, Kim et al. [49] introduced a heat pump system into FCEV thermal management, optimizing parameters such as coolant volume flow rate (VFR), compressor speed, and airspeed. These adjustments reduced cold-start time and energy consumption by 29.9% and 11.3%, respectively, compared to conventional thermal management systems (TMS). However, the study did not explore performance on large-scale fuel cell stacks or under extreme environmental conditions, leaving durability and stack lifespan impacts unaddressed.

Hybrid configurations and advanced EMS offer additional potential for FCEV optimization. Fernandez et al. [50] proposed hybrid FCEV configurations, including plug-in fuel cell hybrid electric vehicles (FC-PHEV) and extended-range fuel cell hybrid electric vehicles (FC-EREV), to extend the driving range and reduce greenhouse gas (GHG) emissions without complete reliance on hydrogen refueling infrastructure. While promising, this study lacked real-world demonstrations and life cycle economic analysis, limiting its practical applicability. Likewise, Li et al. [51] employed deep reinforcement learning (DRL) to optimize battery sizing and energy management, demonstrating improved efficiency. However, further exploration is needed to scale this approach to larger, more complex systems and integrate it with renewable energy sources.

Evaluations of fuel quality and system standards underscore the need for further optimization. Bacquart et al. [52] assessed the impact of hydrogen purity on FCEV performance, finding that even trace contaminants such as CO and H_2S significantly reduce fuel cell efficiency. While their use of synthetic hydrogen in real-world conditions validated fuel cell durability, the long-term impact of hydrogen purity variations in global markets was not addressed. Guo et al. [53] analyzed the FCEV driving range under the revised GB/T 43252-2023 standard, identifying an optimal fuel cell power output of 20–40 kW, representing 45.2% of total operational time. While this benchmark provides practical design guidance, it does not explore renewable hydrogen production integration or life cycle cost implications across entire fleets.

Further operational improvements focus on energy efficiency and grid integration. Li et al. [54] conducted a well-to-wheel (WTW) analysis, comparing battery electric vehicles (BEVs) and FCEVs, revealing that natural gas-powered FCEVs outperform BEVs in energy efficiency and GHG emissions, particularly in cold climates where waste heat is used for cabin heating. However, the study did not investigate how renewable energy integration in hydrogen production could alter outcomes. Lee et al. [55] optimized FCEV thermal management systems by redesigning the radiator to maintain coolant temperatures below 80°C during highway and uphill driving under heavy loads. However, interactions between thermal management and other subsystems, such as air conditioning, remain unexplored.

Finally, Alavi et al. [56] proposed a microgrid concept utilizing FCEVs as dispatchable power generators to enhance grid flexibility. This system integrates renewable energy sources such as wind and solar using predictive control for energy dispatch and hydrogen storage management. While promising, the study primarily focused on electrical integration, overlooking potential thermal energy recovery benefits and scalability to larger grids.

These studies highlight significant advancements in FCEV design, energy management, and operational optimization. However, critical gaps remain in real-world validation, scalability, and life cycle assessments. Future research should integrate interdisciplinary approaches, emphasizing long-term durability, renewable hydrogen integration, and cost-effective scalability to accelerate global FCEV adoption. Addressing these challenges will enhance sustainability and position FCEVs as a cornerstone of future clean transportation systems.

3.2.2. *Energy Management Strategy*

In recent years, EMS has gained increasing attention as a means of enhancing FCEV performance. Zhang et al. [57] introduced the degradation-aware adaptive equivalent consumption minimization strategy (DA-ECMS), which integrates fuel cell and battery degradation models with long short-term memory (LSTM) neural networks. This strategy extends fuel cell and battery lifespan by reducing voltage and capacity degradation by up to 23.2% across various driving cycles, including the worldwide harmonized light vehicle test procedure (WLTP), China light-duty vehicle test cycle (CLTC), and new European driving cycle (NEDC). However, its scalability to real-world scenarios involving varied environmental factors and operational dynamics remains unexplored. Additionally, the study lacks an economic feasibility analysis for commercial-scale deployment of DA-ECMS, limiting its practical applicability.

Uralde et al. [58] proposed a rule-based EMS, validated under the NEDC and WLTC driving cycles, demonstrating efficient hydrogen consumption and battery state-of-charge maintenance. While this approach is simple and effective, its limited scalability and adaptability to complex and real-time driving conditions remain constraints. Furthermore, the strategy was not benchmarked against more advanced optimization- or learning-based EMS approaches, which would provide a comparative evaluation of its effectiveness across diverse operational scenarios.

Advanced machine-learning approaches have also been explored for EMS optimization. Shuai et al. [59] developed a double-deep Q-learning (DDQL)-based EMS, incorporating fuel cell degradation considerations into decision-making processes. This approach reduced fuel cell stack voltage degradation by 50% while maintaining fuel efficiency. However, its robustness in untested driving scenarios remains uncertain, and hardware compatibility and real-time implementation challenges require further investigation. Similarly, Song et al. [60] utilized a deep deterministic policy gradient (DDPG)-based EMS to optimize power allocation between the fuel cell and battery, mitigating thermal risks and degradation while maintaining high energy efficiency. Nevertheless, the scalability of this strategy to different vehicle types and its ability to adapt to varying road and traffic conditions require additional research.

Predictive EMS strategies have shown promising results in leveraging real-time data. Wu et al. [61] proposed a transformer-based predictive EMS (TPEMS) that utilizes real-time traffic data to optimize energy distribution, improving economic efficiency by 4.6% compared to LSTM-based strategies. However, its reliance on detailed traffic datasets presents challenges for large-scale deployment in regions with limited data availability. Additionally, computational efficiency evaluations for real-time applications remain inadequately assessed. Similarly, Pan et al. [62] introduced an EMS integrating a BiLSTM-TCN-SA speed prediction model with Harris Hawk optimization, achieving better fuel cell efficiency and battery durability. However, its dependence on specific driving cycles and the absence of adaptive mechanisms for varying environmental conditions limit its broader applicability.

Innovative methodologies integrating mixed logic dynamic (MLD) and model predictive control (MPC) have also emerged. Luo et al. [63] combined these approaches to optimize energy management in fuel cell-supercapacitor hybrid systems, reducing hydrogen consumption and enhancing fuel cell durability. However, the study lacks experimental validation under dynamic real-world driving conditions and does not address the scalability of MLD models to more complex hybrid configurations. Ji et al. [64] further advanced EMS research by introducing a hierarchical energy management strategy (HEMS) that integrates dynamic programming and Pontryagin's minimum principle. While this strategy enhances fuel efficiency and durability, its dependence on predefined operating conditions reduces its flexibility in unpredictable scenarios, and its economic implications for hydrogen consumption reduction remain underexplored.

Recent studies have also addressed computational challenges in EMS design. Tao et al. [65] proposed an adaptive equivalent consumption minimization strategy (A-ECMS) enhanced with a distributed interior-point method for FCHEVs. This strategy reduces hydrogen consumption and improves fuel efficiency by incorporating adaptive filtering techniques and convex optimization. However, its dependence on convex transformations restricts its applicability to inherently non-convex problems, necessitating further research to extend this approach to increasingly complex real-time dynamic environments. Ren et al. [66] developed a deep reinforcement learning-based predictive EMS (DRL-PECMS), focusing on battery lifespan extension and fuel efficiency, achieving significant hydrogen consumption reductions. Despite these advancements, this strategy requires greater robustness under highly dynamic conditions and integration with renewable energy sources.

Finally, Huy et al. [67] implemented generative adversarial imitation learning (GAIL) to optimize energy scheduling for hydrogen refueling stations, achieving a 29% increase in profitability. While effective in mimicking expert decision-making for real-time applications, its scalability to high-dimensional multi-agent systems and its ability to handle uncertainty in dynamic load conditions remain limited. Zhao et al. [68] proposed a hierarchical EMS incorporating an adaptive moving average filter and deep deterministic policy gradient algorithm, improving fuel efficiency and reducing hydrogen consumption across various driving cycles. However, its sensitivity to filter tuning and its limited exploration of nonlinear load variations highlight areas for further refinement.

Collectively, these studies demonstrate significant advancements in EMS design, showcasing innovative strategies to enhance efficiency, durability, and cost-effectiveness in FCEVs. However, critical gaps remain in developing these strategies for real-world applications, addressing diverse environmental and operational conditions, and conducting comprehensive economic evaluations. Future research should focus on integrating these strategies into holistic systems that account for real-time constraints, scalability, and sustainability to enable practical and widespread FCEV adoption.

3.2.3. *Environmental Sustainability of Fuel Cell Electric Vehicles: Life Cycle Implications*

The environmental sustainability of FCEVs heavily depends on the life cycle impact of their key components and associated energy systems. Recent studies have explored the environmental implications of hydrogen storage, fuel cell systems, and hydrogen production pathways, offering critical insights into potential improvements and existing challenges.

Benitez et al. [69] conducted a detailed LCA of Type IV hydrogen storage tanks, highlighting the significant environmental impact of carbon fiber production, particularly concerning climate change and fossil resource depletion. Their study projected a 46% reduction in climate-related impacts (CO_2-eq) and a 75% decrease in human toxicity by 2050 under optimized conditions, including advancements in carbon fiber production processes and the use of renewable electricity. However, the study did not explore end-of-life recycling solutions for carbon fiber or provide a detailed supply chain emissions analysis for key materials such as epoxy resin. Addressing these gaps would further enhance the sustainability and scalability of hydrogen storage technologies in FCEVs.

In a complementary LCA of polymer electrolyte membrane fuel cell (PEMFC) systems, Usai et al. [70] performed a comprehensive LCA of polymer electrolyte membrane fuel cell (PEMFC) systems used in light-duty FCEVs. Their findings revealed that hydrogen storage tanks and platinum-based catalysts are the primary contributors to global warming potential (GWP), collectively accounting for over 50% of the system's environmental impact. The production of an 80-kW PEMFC system generates approximately 5 tons of CO_2-eq emissions, with 40% arising from the energy-intensive carbon fiber production for hydrogen tanks. Additionally, platinum catalysts impose significant environmental burdens due to energy-intensive mining and processing operations. While prospective scenarios aligned with the U.S. Department of Energy (DOE) targets for 2025 demonstrated a potential GWP reduction of up to 54%, critical gaps remain in data accuracy, recycling solutions for carbon fiber and platinum, and the downstream impact of hydrogen production and distribution.

Expanding the analysis to upstream hydrogen production, Navas-Anguita et al. [71] modelled techno-economic and environmental scenarios for hydrogen production in Spain, emphasizing the transition from natural gas steam reforming to renewable electrolysis and biomass gasification. Their study projected emission reductions of 36–58 Mt CO_2-eq by 2050 under carbon footprint constraints, underscoring the role of green hydrogen in decarbonizing energy systems. However, the analysis did not account for downstream impacts such as hydrogen transportation and distribution, nor did it address potential biomass availability constraints and competition with other sectors. Expanding the scope of future research to incorporate these factors would provide a more comprehensive understanding of hydrogen's role in meeting climate targets and supporting the widespread adoption of FCEVs.

Collectively, these studies underscore the crucial role of advanced materials, green energy inputs, and sustainable production pathways in reducing the environmental impact of FCEV technology. Addressing the identified gaps (including recycling solutions, supply chain emissions, and downstream effects) will be essential to align FCEV advancements with global decarbonization goals and drive large-scale adoption as a sustainable transportation solution.

3.2.4. *Policy and Economic Factors Influencing Fuel Cell Electric Vehicle Adoption*

3.2.4.1. *Economic Viability and Cost Reduction Strategies*

The economic viability of fuel cell electric vehicles (FCEVs) has become a focal point of recent research as stakeholders seek to transition from pilot deployments to large-scale adoption. Chen and Melaina [72] conducted a techno-economic evaluation of FCEVs in comparison to internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs), and battery electric vehicles (BEVs). Their findings project that by 2035, FCEVs would incur 36% higher five-year ownership costs than ICEVs, but 15% lower than BEVs due to reduced initial purchase costs. By 2050, cost parity with ICEVs could be achieved if hydrogen prices fall to $2.5/kg and fuel cell system costs decrease to $30/kW. However, their analysis omits critical variables such as maintenance, insurance, and refueling inconvenience (factors that significantly influence real-world user decisions). Future studies should incorporate a more comprehensive cost framework that includes regional and behavioral dimensions to better inform economic feasibility models.

Complementing this, Li et al. [73] introduced an online cost minimization strategy (CMS) for FCHEVs, which integrates fuel cell and battery degradation models into the vehicle's energy management system. When tested under the Urban Dynamometer Driving Schedule (UDDS), this method effectively reduced hydrogen consumption and extended component life. However, the strategy's applicability remains limited by its narrow validation scope, which excludes high-speed or start-stop driving cycles, variable hydrogen pricing, and feasibility for heavy-duty vehicle use. Expanding CMS validation to account for diverse real-world operating conditions is essential for evaluating its scalability and commercial potential.

Further insights into system-level trade-offs are offered by Moghadari et al. [74], who compared single-stack and multi-stack configurations in FCHEVs. Their results indicate that multi-stack configurations provide enhanced hydrogen efficiency and longer component lifetimes, reducing fuel consumption by 3–4%. However, their study lacks a detailed assessment of the increased complexity and maintenance demands associated with such configurations. Similarly, Wang et al. [75] assessed the total cost of ownership (TCO) for heavy goods vehicles (HGVs) and found that FCEVs are still 37–80% more expensive than ICEVs, mainly due to high capital expenditures (CAPEX). While FCEVs offer advantages for long-haul operations, such as faster refueling and reduced payload penalties compared to BEVs, the analysis does not consider infrastructure investment or supply chain readiness. A more holistic approach to system-level cost modeling is needed for evaluating commercial fleet deployment.

3.2.4.2. Innovations in Hydrogen Production and Decentralized Energy Systems

Younas et al. [19] addressed hydrogen production costs by developing a decentralized solar-powered system that combines microplasma steam reforming and microbubble mass transfer. Their study highlighted steam methane reforming (SMR) as the dominant method (>80% of global supply) due to its low cost, yet criticized its unsustainable CO_2 emissions. Renewable alternatives such as electrolysis, biohydrogen, and photocatalysis offer environmental benefits but are limited by cost and efficiency. Their proposed plasmolysis method offers high energy efficiency (79.2%) at a moderate cost ($6.36/kg), but challenges remain in scale-up, hydrogen-oxygen separation, and grid integration. These findings reinforce the importance of innovating cost-effective and sustainable hydrogen pathways to enable affordable FCEV operation.

3.2.4.3. Policy Design and Financial Incentives

Policy frameworks also play a pivotal role in accelerating FCEV adoption. Teng et al. [76] examined the effectiveness of 140 policy combinations using a generalized Bass diffusion model tailored to heavy-duty fuel cell electric trucks (HD-FCETs) in China. They found that integrated policy mixes (such as hydrogen fuel subsidies, diesel bans, and tax incentives) can increase HD-FCET market share by up to 35.7% while lowering cumulative social costs. However, only 12.39% of the simulated policy combinations achieved both cost-efficiency and high adoption rates. The study stresses the need for class-specific modeling and life-cycle assessment to avoid unintended cost escalations, and suggests that early sales bans coupled with targeted subsidies are the most effective strategies.

Zhao et al. [77] evaluated adoption outcomes in California using the IMPACT model. They demonstrated that financial incentives such as the Clean Vehicle Tax Credit (CVTC) and California's HVIP voucher program had limited effectiveness unless paired with infrastructure development and vehicle availability. Under the most aggressive scenario, FCET adoption rose by only 6–14%, and most gains were negligible without a robust hydrogen refueling network. These findings underscore that incentives alone are insufficient (successful adoption depends on synchronized infrastructure investment, commercial model readiness, and policy timing).

Yin et al. [78] applied a tripartite evolutionary game theory (EGT) model to examine the subsidy efficiency for FCEV logistics vehicles in the Beijing-Tianjin-Hebei city cluster. Their simulations showed that purchase subsidies for consumers were more effective than construction subsidies for hydrogen refueling stations, especially when optimized for local economic conditions. They concluded that dynamic, stakeholder-sensitive subsidy allocation, combined with non-financial incentives such as public awareness campaigns, is essential for maximizing policy effectiveness.

Collectively, these studies demonstrate significant progress in optimizing the economic viability of FCEVs. However, persistent gaps remain in assessing real-world implementation, accounting for infrastructure costs, and understanding user behavior. Future research must adopt dynamic, multidimensional frameworks that integrate financial, technological, and socio-behavioral factors. This comprehensive approach is essential to support evidence-based policymaking, guide industrial investment, and facilitate the transition toward large-scale FCEV adoption as a sustainable transport solution.

3.3. Gap: Critical Unaddressed Areas in Fuel Cell Electric Vehicle Research and Deployment

Despite the notable progress made in FCEV research over the past two decades, several critical gaps persist that hinder the widespread adoption and practical integration of this technology. These gaps are not merely technical but span economic, infrastructural, behavioral, and policy dimensions, each requiring targeted and interdisciplinary interventions.

First, a comprehensive understanding of the total cost of ownership (TCO) for FCEVs remains insufficient. While studies have explored fuel cell efficiency, hydrogen storage, and powertrain optimization, few have developed dynamic, real-world TCO models that incorporate key financial factors such as insurance, maintenance, component degradation, and end-of-life recycling. Moreover, existing models often neglect regional hydrogen price volatility, infrastructure availability, and operational uncertainty (factors essential for decision-making in emerging and resource-constrained markets).

Second, limited real-world validation presents a significant research gap. Many promising advancements, especially in energy management strategies (EMS) involving deep reinforcement learning or predictive control, remain confined to simulations or controlled test environments. These approaches lack sufficient exposure to unpredictable driving patterns, climate variability, and user behavior diversity, which are critical for assessing their robustness and adaptability under real-world operational conditions. In addition, there is a paucity of field data to validate degradation-aware strategies that claim to enhance durability and lifecycle efficiency.

Third, although technological breakthroughs in hydrogen production, such as renewable electrolysis and plasmolysis, have been documented, there is a persistent lack of integration between upstream innovation and downstream deployment logistics. Issues related to hydrogen distribution bottlenecks, regional energy grid limitations, lifecycle emissions of hydrogen supply chains, and the scalability of refueling stations in both urban and rural settings remain underexplored. These infrastructural uncertainties contribute to slow deployment and high operating costs.

Fourth, a behavioral and policy gap is evident. While several studies highlight the role of fiscal incentives and regulatory bans, few have modeled the interplay between consumer perception, safety concerns, and policy coordination. There is limited empirical research on how public acceptance evolves with infrastructure readiness, nor are there frameworks evaluating the effectiveness of combined financial and non-financial incentives (e.g., awareness campaigns, vehicle accessibility). Without addressing these soft factors, technological readiness alone is unlikely to yield high adoption rates.

Finally, most existing literature treats the above gaps in isolation. A major deficiency is the lack of systemic, multi-dimensional approaches that unify techno-economic modeling, infrastructure planning, behavioral analysis, and policy design into cohesive roadmaps for FCEV deployment. As a result, potential synergies across sectors remain untapped, and the global scaling of FCEV technologies is delayed.

To overcome these barriers, future research must adopt integrated and empirical approaches, incorporating real-world pilot studies, geographically diverse datasets, and dynamic simulations that reflect actual market behaviors. Furthermore, research must emphasize longitudinal assessment frameworks that evaluate economic, environmental, and behavioral impacts across the FCEV lifecycle. Bridging these critical gaps will be essential to elevate FCEVs from promising prototypes to scalable solutions within sustainable transportation ecosystems.

3.4. Evidence for Practice: Real-World Performance and Practical Applications of Fuel Cell Electric Vehicles

Wipke, K. et al. [79], through the U.S. Department of Energy project, provided valuable insights into the real-world performance of FCEVs and hydrogen refueling infrastructure over seven years. By deploying 183 FCEVs and 25 hydrogen refueling stations, the study recorded significant advancements, including enhanced fuel cell durability, improved system reliability, a driving range of up to 250 miles, and reduced hydrogen refueling time. These findings underscore the strong commercial readiness of FCEV technology. However, while the study confirmed technical feasibility, it did not thoroughly examine cost-effectiveness for large-scale commercialization, particularly in emerging markets. Additionally, real-world user adoption behaviors and challenges in expanding hydrogen infrastructure remain underexplored, highlighting key areas for further investigation.

Sun et al. [80] assessed the adaptability of FCEVs and BEVs to real-world driving cycles in China using simulations and dynamometer testing. Their findings indicate that FCEVs outperform BEVs in regenerative braking efficiency and dynamic response across various driving conditions, emphasizing their potential for diverse mobility scenarios. However, the study did not evaluate long-term component wear under varying environmental factors, which is critical for assessing real-world durability. Furthermore, the economic implications of integrating this technology into large-scale mobility systems were not addressed, leaving gaps in cost considerations and operational feasibility.

Tiedemann et al. [81] explored the potential of FCEVs as decentralized energy solutions, leveraging waste heat and electricity generation to meet local energy demands. Their findings suggest that waste heat from FCEVs can supply up to 49% of thermal demand, demonstrating their dual functionality as both a mobility and energy solution. While the study confirms technical feasibility, key challenges remain, including hydrogen supply chain scalability, seasonal energy demand variations, and the economic viability of FCEV integration in residential applications. Addressing these gaps is essential for wider-scale implementation and policy-driven adoption.

Legala et al. [82] applied machine learning to model hybrid power system dynamics in Toyota Mirai, analyzing performance under various driving cycles. Their neural network model achieved high accuracy in predicting system behaviors, including voltage fluctuations and temperature variations, offering valuable insights for diagnostics and system design. However, the model is limited to specific driving cycles and lacks validation under extreme environmental conditions, which could significantly impact system performance. Additionally, practical integration into vehicle control systems and real-world reliability testing remain unexplored, restricting its direct implementation in commercial FCEVs.

Overall, these findings highlight significant technological advancements and the practical application potential of FCEVs across various scenarios. However, key challenges remain in scalability, cost analysis, and broader system integration, which are critical for real-world implementation and pilot projects. Future research should focus on addressing these limitations to facilitate the widespread adoption of FCEVs, supporting sustainable mobility and the global energy transition.

3.5. Recommendation: Research Priorities and Practical Interventions

To bridge the identified gaps and accelerate the adoption of FCEVs, targeted research efforts and practical interventions are crucial. Comprehensive economic modeling must be a top priority. Future studies should integrate dynamic TCO models, encompassing a broader spectrum of costs, including maintenance, insurance, and end-of-life recycling processes. These models should account for regional variations in hydrogen prices, infrastructure deployment, and market conditions, providing actionable insights for policymakers and industry stakeholders. Additionally, techno-economic analyses should evaluate the trade-offs in adopting green hydrogen production pathways, such as renewable electrolysis and biomass gasification, to identify cost-reduction levers that align with global decarbonization goals.

Real-world validation of EMS is another critical focus area. While machine learning and reinforcement learning-based EMS have demonstrated significant potential in controlled environments, their resilience and adaptability to real-world conditions require further exploration. Research should prioritize testing EMS under diverse operational conditions, including extreme climates, high-speed urban traffic, and heavy-load scenarios. Moreover, evaluating hardware compatibility constraints and powertrain reliability impacts is essential to ensure feasibility for large-scale implementation. Alongside EMS improvements, hydrogen infrastructure and supply chain optimization remain urgent challenges. Scalable solutions for green hydrogen production, including renewable energy integration and localized hydrogen hubs, must be prioritized. Additionally, the LCA of the hydrogen supply chain should address downstream impacts, such as emissions from distribution networks and the scalability of refueling stations in both urban and rural areas.

Furthermore, innovation in material recycling and resource recovery is vital for enhancing FCEV sustainability. Developing closed-loop recycling systems for critical components, such as carbon fiber hydrogen tanks and platinum catalysts, will reduce environmental impact and improve material cost efficiency. Parallel efforts should focus on coordinated policy measures and consumer engagement strategies to overcome adoption barriers. Research must assess the effectiveness of subsidies, tax incentives, and infrastructure investments, while behavioral studies can provide insights into consumer perceptions and willingness to adopt FCEVs. Lastly, large-scale pilot projects integrating FCEVs into public transportation, logistics, and residential energy systems should be prioritized. These initiatives will generate critical data on operational efficiency, scalability, and economic feasibility while demonstrating the tangible benefits of FCEVs to policymakers, investors, and the public. Addressing these research priorities will establish a strong foundation for the widespread adoption of FCEVs, contributing to global decarbonization efforts and driving a sustainable transition in the transportation and energy sectors.

4. Limitations

While this bibliometric analysis provides valuable insights into the research landscape of FCEV performance using the PAGER framework, several methodological limitations must be acknowledged to contextualize the findings and guide future research. First, this study relies solely on Scopus due to its comprehensive coverage and structured metadata. However, the exclusion of databases such as Web of Science and IEEE Xplore may have resulted in the omission of studies relevant to interdisciplinary or engineering focus. These limitations may result in an incomplete representation of the global FCEV research landscape, overlooking contributions from niche or regional journals. Future reviews should consider a multi-database strategy for more comprehensive coverage.

Furthermore, the descriptive nature of bibliometric methods constrains the ability to infer causality or assess the direct impact of research trends on real-world FCEV advancements. While bibliometric mapping effectively identifies patterns and connections among research topics, authors, and geographic distributions, it lacks the depth to capture the complex interactions between technological advancements, policy frameworks, and economic constraints without integrating mixed-method approaches, such as qualitative analysis or case studies.

Another significant limitation lies in the simplified categorization of keywords and clustering generated by bibliometric mapping tools such as VOSviewer. This approach may oversimplify intricate relationships between research themes, potentially leading to the reduction of critical interdisciplinary topics (such as hydrogen supply chain logistics or renewable energy integration in FCEV systems) into broad clusters, thus diminishing the accuracy and granularity of the findings. Additionally, advanced text mining techniques were not employed in this study, despite their potential to identify emerging themes and latent connections across multiple disciplines. The temporal scope (2005–2024) also introduces time-related biases, as earlier foundational studies and recent high-impact works may be underrepresented. The reliance on citation-based metrics to assess research influence favours older publications, possibly overlooking emerging yet highly impactful studies that have not yet accumulated significant citations.

Although in principle, the shortcomings in this study may reduce the reliability and applicability of bibliometric analysis, by using the PAGER framework, this bibliometric study becomes more than just a mapping of literature (it is a strategic analysis that interprets not only what has happened, but also what is important, what is missing, and where the field should go next). This bridges the gap between quantitative bibliometric data and theory-based qualitative interpretation, making the findings more in-depth, usable, and policy-relevant. However, future research must still expand data collection to include multiple databases, incorporate mixed-method approaches, implement advanced text mining tools, and broaden the temporal scope. These improvements will enable bibliometric studies to provide a more comprehensive and actionable roadmap for accelerating technological advancements in FCEVs while ensuring a robust and unbiased representation of the evolving research landscape.

5. Conclusion

This bibliometric analysis systematically maps the evolution of fuel cell electric vehicle (FCEV) performance research from 2005 to 2024 through the application of the PAGER framework. The findings reveal a clear progression across three research phases (early exploration (2005–2008), gradual growth and refinement (2009–2019), and rapid expansion and technological maturity (2020–2024)) highlighting significant advancements in energy management strategies, fuel cell durability, hydrogen infrastructure, and smart grid integration. Through keyword clustering, institutional mapping, and citation analysis, this study identifies the key contributors, emerging themes, and influential publications shaping the FCEV research landscape.

Despite these advancements, several critical gaps persist that impede the large-scale deployment of FCEVs. These include the lack of dynamic and region-sensitive total cost of ownership (TCO) models, limited real-world validation of advanced energy management systems (EMS), and persistent challenges in hydrogen infrastructure scalability. Furthermore, the fragmented integration of technological innovation, behavioral adoption patterns, and policy interventions underscore the need for systemic, interdisciplinary research approaches.

This study contributes practical insights by evaluating real-world evidence and highlighting the necessity for synchronized pilot programs, green hydrogen integration, advanced recycling strategies, and user-centred policy designs. Moving forward, future research must address these multidimensional challenges through empirical validation, techno-economic modeling, and stakeholder-inclusive frameworks. By doing so, the FCEV sector can be positioned as a cornerstone of global decarbonization efforts, offering a scalable, sustainable, and resilient solution for zero-emission mobility.

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Author's Declaration

Authors' contributions and responsibilities

Yusuf Dewantoro Herlambang: Formal analysis, Writing – review & editing, Validation, Funding acquisition; Nanang Apriandi: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing review & editing, Software; Komang Metty Trisna Negara: Investigation, Formal analysis, Writing – review & editing; Rani Raharjanti: Conceptualization, Data curation, Visualization; Lily Maysari Angraini: Conceptualization, Formal analysis, Writing – review & editing, Supervision; Abdul Syukur Alfauzi: Supervision; Marliyati: Project administration.

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Competing interests

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