

Hydrogen energy in transportation systems: a scientometric analysis of global research trends, open challenges, and future research opportunities

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ABSTRACT

Hydrogen energy has emerged as a strategic option for decarbonizing transport segments that are difficult to electrify directly. Yet the integrated intellectual structure, collaboration networks, thematic evolution, and emerging digital frontiers of this rapidly expanding research field remain insufficiently characterized. This study addresses that gap through a comprehensive scientometric analysis of 1,699 Scopus-indexed journal articles on hydrogen energy in transportation published between 2000 and 2025. An integrated multi-tool workflow comprising Bibliometrix, VOSviewer, and Python with cross-tool validation is employed. Results reveal a compound annual growth rate of 18.82%, with China, Germany, and the United Kingdom as the principal research contributors. Three dominant knowledge clusters are identified: hydrogen production and storage infrastructure (Technology Readiness Level 4 to 8), fuel cell vehicle technologies and energy management (TRL 6 to 9), and electric and hydrogen-electric hybrid system integration (TRL 4 to 9). Keyword burst analysis identifies an emerging digital convergence frontier. Green hydrogen, machine learning, and digital twin are the fastest-growing terms in the 2021 to 2025 period. Blockchain, IoT, and quantum computing also show notable keyword growth, though their absolute frequencies remain low and are treated as prospective research directions. The findings are contextualized against documented techno-economic progress, including boundary-dependent electrolyzer cost-reduction pathways and uneven hydrogen-refueling infrastructure deployment. The study advances a systems-integration perspective. This field has matured from isolated component studies into an interconnected knowledge system spanning production, infrastructure, vehicle technology, and digital intelligence. The findings offer actionable implications for researchers, engineers, and policymakers advancing the global hydrogen transition.

1. Introduction

The decarbonization of transportation systems has become a central challenge in global climate mitigation. Transport remains a major source of energy-related carbon dioxide emissions, and several segments, especially long-haul road freight, shipping, and aviation, remain difficult to decarbonize through direct electrification alone [1,2]. These pressures have intensified the search for clean, secure, and scalable energy carriers that can support sustainable mobility transitions.

Hydrogen energy has emerged as a prominent option within this

context. Hydrogen is an energy carrier producible through multiple pathways; its climate benefit depends strongly on the production route, as green hydrogen produced through renewable electricity supports low-emission transport pathways, whereas fossil-derived hydrogen without effective carbon management offers much smaller decarbonization benefits [3,4]. Hydrogen's cross-sectoral flexibility links renewable electricity, industrial systems, storage infrastructure, and transport applications, making it relevant to broader energy-system integration [5,6].

From a technical perspective, hydrogen is relevant to transport

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applications requiring long range, high payload, rapid refueling, or continuous operation. Conversion routes are mode-specific and include fuel cell electric propulsion, hydrogen combustion, hydrogen-derived fuels, and hydrogen-battery hybrid configurations [4,7–12]. Hydrogen refueling infrastructure is central to the deployment pathway, as station design, compression, storage, dispensing, safety, and permitting requirements directly affect practical adoption [13,14]. Hydrogen is best understood as complementary to battery-electric solutions, particularly where battery mass, charging time, range, or duty-cycle requirements constrain direct electrification [15,16].

At the system level, hydrogen enables large-scale energy storage, supports sector coupling, and facilitates integration of variable renewable energy sources, connecting transport networks with power systems and industrial clusters [4,5]. These functions have elevated hydrogen from a niche alternative fuel to a strategic element of clean-energy planning. National and regional hydrogen strategies commonly emphasize renewable production, refueling.

infrastructure, fuel cell vehicle deployment, and market-creation mechanisms [4,17], and the scientific literature has expanded accordingly across production, storage, fuel cell design, environmental assessment, techno-economic evaluation, and policy design [4,5,14,18].

Despite this growing body of work, the research landscape remains fragmented. Technical reviews provide detailed insight into individual components of the hydrogen value chain but do not quantify the intellectual structure of the field, the evolution of research themes, or the configuration of scientific collaboration networks [4,5,14,18]. Existing bibliometric studies have examined the hydrogen economy, green hydrogen, fuel cells, and hydrogen storage safety, but their scopes are often broader than transportation or narrower than a multimodal hydrogen mobility system [19–23]. As a result, the relationships among technological development, policy discourse, multimodal transport applications, and emerging digital research frontiers remain insufficiently integrated, making it difficult to identify influential research clusters, assess knowledge diffusion patterns, or understand how the field responds to policy and market signals over time.

1.1. Related bibliometric studies and positioning of the present work

Several bibliometric and scientometric studies have examined hydrogen energy research from different perspectives, providing important baselines for understanding the evolution of the hydrogen economy, green hydrogen technologies, hydrogen fuel cells, and safety issues related to hydrogen storage and transportation. However, their scopes differ substantially from the present study. Table 1 compares the most relevant prior studies and positions the present work within this literature.

As shown in Table 1, prior studies have made important contributions to hydrogen research mapping but do not jointly characterize hydrogen mobility as an integrated multimodal system spanning road, rail, maritime, aviation, infrastructure, technology readiness, collaboration structure, and emerging digital research signals. The present study addresses this gap by combining performance analysis, science mapping, thematic evolution, keyword-burst analysis, technology-readiness interpretation, and cross-tool validation within a single 2000–2025 Scopus-indexed corpus.

The present study makes five specific contributions.

- (1) **Comprehensive multimodal transport scope:** The analysis covers hydrogen-related research across road, rail, maritime, and aviation applications, providing a unified view of hydrogen mobility research rather than a segment-specific perspective.
- (2) **Extended temporal coverage:** The 2000–2025 time window captures the progression from early exploratory research to the post-2020 acceleration associated with national hydrogen strategies, refueling infrastructure planning, and deployment-oriented research.
- (3) **Validated multi-tool methodology:** The integration of Bibliometrix, VOSviewer, and Python analytics with quantitative cross-tool validation provides an explicit robustness check for thematic cluster interpretation.
- (4) **Evidence-based treatment of digital frontiers:** Emerging digital technologies, including artificial intelligence, digital twins,

Table 1

Comparative overview of prior bibliometric and scientometric studies related to hydrogen energy, fuel cells, hydrogen storage and transportation safety, and hydrogen mobility. The present study is positioned in the final row.

Study	Database	Period	Documents	Scope	Methods	Main distinction from the present study
Yap and McLellan [19]	Scopus + LEXIS + IEA projects	1972–2020	509 academic studies; 11,125 media articles; 383 projects	Hydrogen economy research, development, media expectations, and demonstration projects	Bibliometric keyword/co-occurrence analysis; content analysis; historical mapping	Broad hydrogen-economy focus; not specific to transportation applications
Kar et al. [20]	Scopus	Five-decade coverage to 2021	1,275	Hydrogen economy, including production, storage, transportation, application, and policy	VOSviewer; keyword and cluster analysis; field-weighted citation impact; usage count	Transportation is included within a broader hydrogen-economy framework but is not analyzed as an integrated mobility system
Osman et al. [21]	SCIE + Scopus	1990–2023	6,536	Hydrogen energy research with emphasis on green hydrogen technologies	Bibliometric indicators; thematic clustering; impact factor, h-index, total citations, citations per article PRISMA; Biblioshiny; VOSviewer; thematic evolution analysis	Focused on green hydrogen and energy-system research rather than transportation-specific applications
Agyekum et al. [22]	Scopus	2003–2023	3,107	Hydrogen fuel cells with a focus on vehicle applications		Vehicle- and fuel-cell-centered; limited coverage of rail, maritime, aviation, and infrastructure-system integration
Tang et al. [23]	WoS + Scopus + ScienceDirect	Since 2007	948	Hydrogen storage and transportation safety	Bibliometric mapping; cooperation-network analysis; hotspot and evolution analysis	Safety- and materials-oriented; does not provide a comprehensive hydrogen mobility-system analysis
Present study	Scopus	2000–2025	1,699	Hydrogen energy across road, rail, maritime, and aviation transportation systems	Bibliometrix + VOSviewer + Python; PRISMA screening; Cohen's κ; cross-tool Jaccard validation; keyword-burst analysis; TRL mapping	Integrated multimodal hydrogen-transportation focus; single-database and English-language article corpus; limitations are discussed in Section 7

blockchain, IoT, and quantum computing, are discussed according to their keyword growth and absolute frequency, and are framed as prospective research directions rather than mature bibliometric findings.

- (5) **Systems integration perspective:** The study interprets hydrogen transportation research as an interconnected knowledge system spanning production, storage, infrastructure, vehicle technology, sustainability assessment, and digital intelligence.

1.2. Research objectives

The study pursues four main objectives.

- (1) To quantify the growth trajectory and global distribution of hydrogen transportation research across the 2000–2025 period.
- (2) To identify the most influential institutions, journals, and funding sources, and to characterize the structure of international collaboration networks using quantitative network metrics.
- (3) To map the dominant research themes, examine their evolution across successive time periods, and link thematic clusters to technology readiness levels and industry adoption stages.
- (4) To identify emerging digital research frontiers, quantify their bibliometric trajectories using keyword trend analysis, and outline future research directions grounded in bibliometric evidence and techno-economic context.

By integrating large-scale bibliometric analysis with critical qualitative synthesis, techno-economic contextualization, and explicit methodological validation, this paper provides a comprehensive and reproducible overview of hydrogen energy research in transportation systems. The findings support evidence-based decision-making by highlighting collaboration patterns, research gaps, and strategic priorities for researchers, engineers, and policymakers engaged in the global hydrogen transition.

The remainder of this paper is organized as follows. Section 2 presents a taxonomy of hydrogen energy in transportation, covering technological, infrastructural, and policy dimensions. Section 3 describes the methodological framework, including database selection and justification, search query design and sensitivity analysis, PRISMA-based screening with inter-screener validation, data cleaning with quantitative impact assessment, multi-tool analytical procedures, cross-tool validation, and network metrics. Section 4 reports the bibliometric results,

including descriptive statistics, performance indicators and science mapping analyses encompassing co-authorship networks, bibliographic coupling, keyword co-occurrence with technology readiness mapping, and thematic evolution with keyword trend analysis. Section 5 discusses the key findings through a systems integration lens, including techno-economic contextualization, comparison with battery-electric pathways, analysis of contradictions and regional disparities, and actionable recommendations for researchers, industry stakeholders, and policy-makers. Section 6 outlines future research directions, with digital frontiers framed according to their bibliometric maturity and prospective relevance. Section 7 summarizes the principal findings, conceptual contribution, limitations, and avenues for further research.

2. Taxonomy of hydrogen energy in transportation

Hydrogen energy in transportation is best understood as an integrated value-chain system rather than as an isolated vehicle technology. It connects hydrogen production, storage and distribution, refueling and corridor infrastructure, and end-use applications across road, rail, maritime, and aviation modes. These technical layers are shaped by policy, economics, safety regulation, standards, public acceptance, and system-level planning [4,5]. Fig. 1 presents the conceptual taxonomy used in this study. The taxonomy shows how production pathways, infrastructure, transport applications, and governance mechanisms interact to support low-carbon mobility when hydrogen is produced, distributed, and used through appropriately designed low-emission systems.

Hydrogen Production. Hydrogen production forms the upstream foundation of the transportation hydrogen value chain because the production route strongly influences lifecycle emissions, cost, scalability, and the overall sustainability of downstream mobility applications [3,24,25]. Production routes are commonly grouped by energy source and carbon-management pathway. Green hydrogen is produced through water electrolysis powered by renewable electricity, including solar, wind, and hydropower. It has very low direct operational emissions, although its full lifecycle performance depends on electricity source, electrolyzer efficiency, system boundaries, and infrastructure requirements [3,26–28]. Blue hydrogen is generally produced from natural gas through steam methane reforming or related reforming routes combined with carbon capture, utilization, and storage; it can reduce emissions relative to unabated fossil hydrogen but depends on methane-leakage control, carbon-capture efficiency, and the availability of

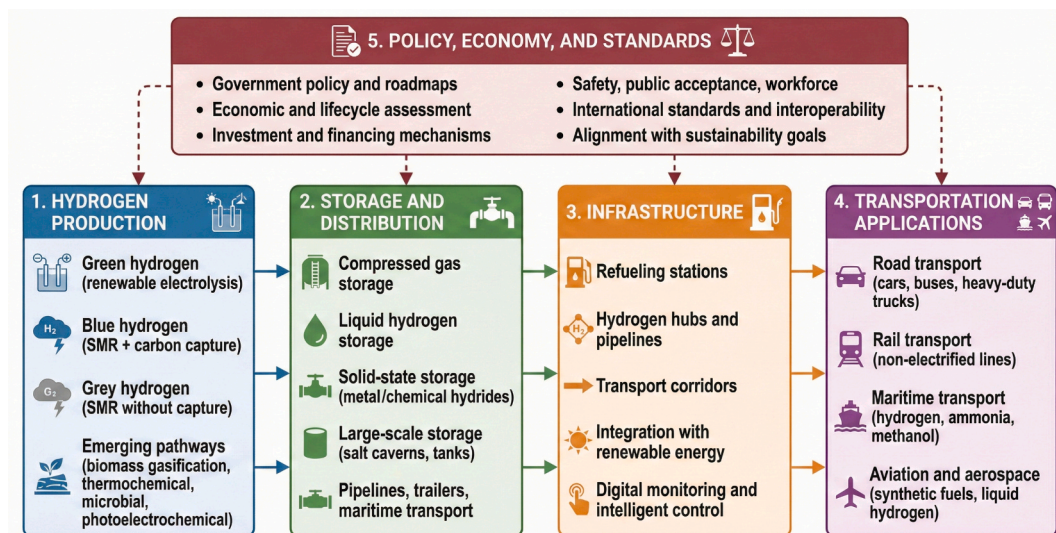


Fig. 1. Conceptual taxonomy of hydrogen energy in transportation systems. The diagram classifies the main value-chain layers linking hydrogen production, storage and distribution, refueling infrastructure, transport applications, and policy-economic frameworks.

capture and storage infrastructure [29,30]. Grey hydrogen uses similar fossil-based reforming routes without carbon capture and remains economically established because of existing industrial infrastructure and lower near-term production cost, but it is not a low-carbon option [31].

Beyond the conventional color taxonomy, recent studies examine advanced and biomass-based pathways that may contribute to cleaner hydrogen systems under appropriate feedstock and process conditions. Thermochemical and syngas-upgrading routes include water–gas shift reactions used to enrich hydrogen and reduce carbon monoxide in carbon-derived syngas [32]. Biohydrogen studies examine dark fermentation and biomass-derived substrates, including metabolic-engineering strategies and vinicultural biomass conversion [33,34]. Photo- and electrochemical biomass oxidation and electrocatalytic water-splitting materials, including layered double hydroxide catalysts, are also being investigated as routes for sustainable hydrogen generation [35,36]. These production pathways show that hydrogen mobility cannot be evaluated only at the vehicle level; it must be assessed through the upstream energy source, conversion pathway, carbon intensity, cost trajectory, and integration with renewable power systems.

Hydrogen Storage and Distribution. Storage and distribution connect production sites with transport demand centers and therefore determine the safety, efficiency, cost, and reliability of hydrogen mobility systems. On-board storage options include high-pressure compressed gas tanks, cryogenic liquid hydrogen systems, and solid-state or material-based storage using metal hydrides, chemical hydrides, or sorbent materials [4,37–39]. These approaches differ in gravimetric and volumetric energy density, boil-off or compression requirements, refueling characteristics, cost, and safety-management needs. Large-scale and stationary storage can involve surface tanks, pressurized vessels, or underground storage options, while system-level supply chains must balance production location, demand density, delivery distance, and temporal variability in renewable electricity output [37,40,41].

Distribution is carried out through pipelines, compressed-gas tube trailers, liquid hydrogen tankers, or hydrogen carriers for longer-distance transport. Pipeline strategies are especially relevant for high-volume industrial clusters and corridor-based deployment, but they require dedicated attention to materials compatibility, leakage control, embrittlement risk, monitoring, and network planning [38,42]. The reliability of these networks depends on safety management, optimized logistics, continuous monitoring, and loss reduction. Current research therefore focuses on improving storage materials, compression and liquefaction efficiency, carrier conversion pathways, and system-level coordination between supply, storage, refueling demand, and transport operations.

Infrastructure. Hydrogen infrastructure forms the physical backbone of transportation deployment. It links production plants, storage assets, pipelines or delivery networks, refueling stations, hydrogen hubs, and end users [14,43]. Refueling-station deployment depends on station location, demand forecasting, compression and dispensing capacity, storage configuration, safety distances, permitting requirements, and integration with renewable electricity or local energy systems [14,44]. Modern infrastructure planning combines spatial modeling, supply-chain optimization, techno-economic assessment, lifecycle considerations, and reliability analysis to identify station layouts and corridor-development strategies that can support early utilization while limiting stranded-asset risk [40,45,46].

Urban systems require denser station coverage for buses, taxis, municipal fleets, and delivery vehicles, whereas intercity and freight systems require corridor-oriented infrastructure for long-distance logistics. Hydrogen pipeline and hub development is therefore closely connected to industrial clusters, port areas, freight corridors, and renewable-resource regions [42]. At the interface with the electricity sector, hydrogen storage can also be embedded in renewable microgrids and hybrid energy systems, but such uses should be treated as energy-

system integration contexts rather than direct evidence of transport-mode superiority [47]. As infrastructure scales up, interoperability, harmonized refueling protocols, public investment, and coordinated regional planning become essential to avoid fragmented networks. Standards and codes from organizations such as ISO, IEC, SAE, and CEN/CENELEC are particularly important for refueling-station safety, quality, permitting, and vehicle–station compatibility [13].

Transportation Applications. Hydrogen can serve transportation through several conversion routes, including fuel cell electric propulsion, hydrogen internal combustion, turbine-based propulsion, synthetic hydrogen-derived fuels, and hybrid hydrogen–battery configurations. Its suitability is mode-specific and depends on range, payload, duty cycle, refueling time, onboard-storage constraints, infrastructure availability, and the carbon intensity of the hydrogen supply chain [4,11]. In road transport, fuel cell electric vehicles are the most mature and widely discussed hydrogen application, especially for buses, fleet vehicles, and heavy-duty trucks where fast refueling and long range may be operationally valuable [7,12,22,48]. These vehicles convert hydrogen into electricity through fuel cells to power electric motors; the vehicle tailpipe emits water, although lifecycle emissions still depend on the upstream hydrogen pathway [18,48,49].

In rail systems, hydrogen fuel cell electric trains are being considered as alternatives to diesel traction on non-electrified routes where full overhead electrification may be costly or impractical [8]. In maritime transport, hydrogen can be used directly or converted into hydrogen-derived fuels such as ammonia or methanol for shipping applications, but fuel storage, safety, engine compatibility, port infrastructure, and fuel-supply logistics remain critical constraints [9,50]. In aviation, hydrogen is being assessed for direct combustion, fuel cell auxiliary systems, and synthetic aviation fuels, with liquid hydrogen storage, aircraft integration, and turbine or fuel-cell system performance remaining major technical challenges [10,11,51]. These applications demonstrate that hydrogen has broad multimodal potential, but deployment should be framed according to mode-specific readiness, infrastructure requirements, and lifecycle performance rather than as a universal replacement for direct electrification.

Practical deployment depends on overcoming challenges related to fuel-supply logistics, storage volume and mass, refueling time, cost, safety validation, and operational reliability. Demonstration fleets, pilot corridors, port trials, rail pilots, and aviation technology programs are therefore essential for validating performance under real operating conditions before large-scale commercialization.

Policy, Economy, and Standards. The success of hydrogen transportation depends on policy and economic frameworks that reduce market risk, support infrastructure investment, and align hydrogen production with decarbonization goals [17,52]. Government policies influence adoption through subsidies, carbon pricing, low-carbon fuel standards, public procurement, and infrastructure co-financing. Economic analysis focuses on reducing production cost, improving refueling-station utilization, and evaluating lifecycle emissions across different transport applications [18,53,54]. Social and institutional factors are equally central: public acceptance, safety awareness, workforce training, and transparent permitting affect the pace of infrastructure rollout. Refueling-station standards and codes ensure safety, fuel quality, and interoperability across national systems [13]. Alignment with the Sustainable Development Goals, especially Goals 7, 11, and 13, supports the policy framing of hydrogen mobility but should be presented as an interpretive sustainability linkage rather than direct proof of deployment impact [55].

This taxonomy demonstrates that hydrogen transportation is an integrated socio-technical system combining production, storage, distribution, infrastructure, vehicle technologies, policy, economics, and standards. Each layer affects the others: low-carbon production is insufficient without safe distribution infrastructure, while vehicle deployment cannot scale without reliable supply chains and harmonized standards. Digital tools such as artificial intelligence, digital twins, and

system modeling may strengthen forecasting, diagnostics, safety monitoring, and decision-making across the value chain.

Fig. 2 summarizes this multidimensional systems perspective, visualizing how production pathways, storage, distribution, transport applications, digital enablers, and policy mechanisms form an interconnected ecosystem. Scalability depends not only on technology readiness but also on coordinated planning of supply corridors, refueling coverage, safety standards, and regional policy alignment.

3. Methodology

This study applied a systematic bibliometric methodology to examine global research on hydrogen energy in transportation systems. The workflow integrated database selection, search query design and validation, data retrieval, PRISMA-guided screening, inter-screener reliability assessment, data cleaning, multi-tool bibliometric analysis, and cross-tool validation. Each step was designed to ensure transparency, reproducibility, and scientific rigor. Fig. 3 presents the overall methodological workflow.

3.1. Database selection

Scopus was selected as the primary bibliographic source for six complementary reasons. First, Scopus provides broad peer-reviewed journal and citation coverage. Comparative bibliographic-database studies show that Scopus and Web of Science differ in source coverage, journal inclusion, and disciplinary representation; this difference is relevant for an interdisciplinary field such as hydrogen transportation research [56,57]. Second, comparative bibliographic-database studies show that Scopus provides broad coverage and curated metadata suitable for bibliometric research, including structured author, affiliation, document, source, and citation fields [57,58]. Third, Scopus subject-area codes allow a transparent domain-level screening step, which is useful for excluding records classified only in non-transport or non-energy domains. Fourth, Scopus export formats are directly compatible with the Bibliometrix and VOSviewer workflows used in this study [59,60]. Fifth, Scopus is widely used in bibliometric

and science-mapping studies, which improves methodological comparability with prior work [61,62]. Sixth, Dimensions was retained as a reference source rather than the primary corpus because comparative database studies show that it covers broader scholarly and research objects beyond the peer-reviewed journal-article corpus targeted here; these broader source types are valuable for discovery but make raw record counts less directly comparable with a corpus restricted to original peer-reviewed journal articles [57,58].

To substantiate this selection, Table 2 presents a structured comparison of Scopus, WoS, and Dimensions for an equivalent query applied to hydrogen energy in transportation. All three platforms were queried on the same retrieval date using identical core terminology, with equivalent language, document-type, and subject-area filters applied where platform functionality permitted.

The approximately 88% WoS overlap and 74% Dimensions overlap reported in Table 2 are therefore interpreted as query-specific robustness checks rather than as claims about universal database coverage. Records unique to WoS and Dimensions were inspected at the title and source level. Their exclusion did not materially alter the principal findings of performance analysis, network mapping, or thematic clustering at the scale of this study. This residual single-database limitation is acknowledged explicitly in Section 7.

3.2. Data collection and search query design

Data were retrieved on 29 December 2025, covering January 2000 to December 2025. This period captures the transition of hydrogen transportation research from early proof-of-concept studies toward deployment-oriented work on vehicles, infrastructure, aviation, and multimodal transport applications [4,11].

The Boolean search strategy was structured in two conceptual layers. The first layer specified hydrogen-transport technology terms as title-abstract-keyword (TITLE-ABS-KEY) fields. The second layer required co-occurrence with transport-mode terms using AND logic, ensuring that retrieved records addressed hydrogen within a mobility context rather than isolated production, storage, or industrial chemistry settings. The keyword-and-year component of the search identified the broad

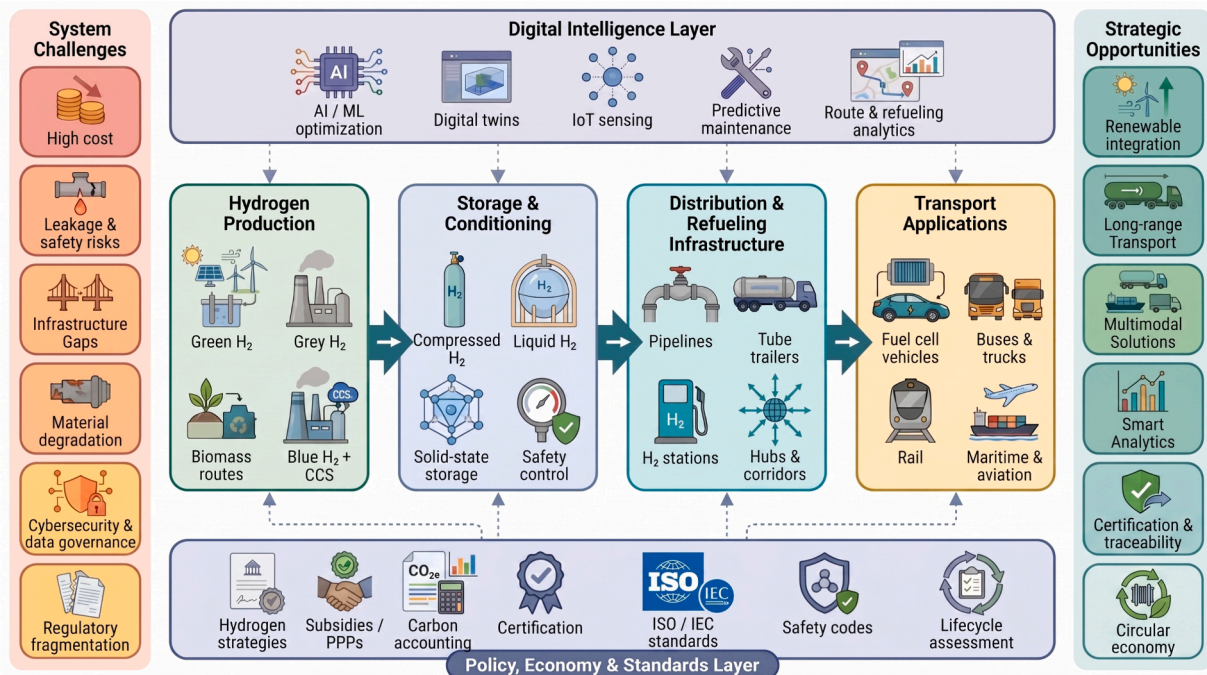


Fig. 2. Conceptual systems map of hydrogen energy in transportation. The figure summarizes the interconnected domains of hydrogen production, storage and conditioning, distribution and refueling infrastructure, transport applications, digital enablers, and policy frameworks.

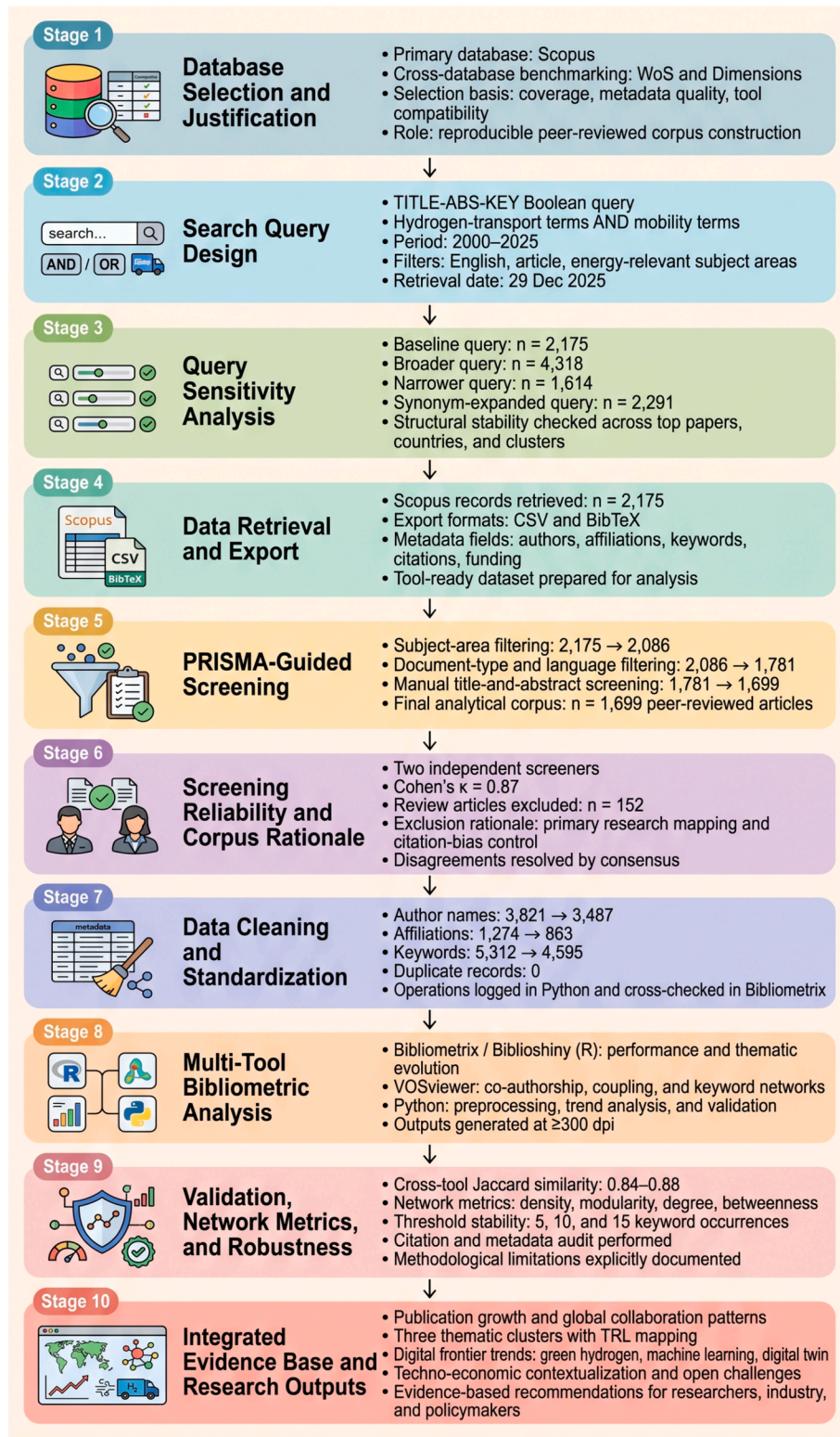


Fig. 3. Methodological workflow for the scientometric analysis.

candidate set. The complete operational Scopus expression, including publication- year limits, document-type restriction, language restriction, and subject-area limiters, is presented in Table 3. For transparency and reproducibility, the effects of these predefined filters were documented stepwise in the PRISMA screening workflow, as shown in Fig. 4 and Tables 5–6. Thus, Table 3 provides the reproducible Scopus search expression, whereas the PRISMA diagram reports the sequential record-

accounting process used to construct the final analytical corpus.

The keyword-and-year search component identified 2,175 candidate records, which were exported in CSV and BibTeX formats for compatibility with multiple analytical tools. Predefined subject-area, document-type, language, and manual relevance criteria were then applied and documented sequentially for PRISMA transparency. Conference papers, review articles, book chapters, editorials, notes, letters, non-English

Table 2

Comparative assessment of Scopus, Web of Science, and Dimensions for hydrogen energy in transportation research (retrieval date: 29 December 2025).

Criterion	Scopus	Web of science	Dimensions
Records retrieved (raw)	2,175	1,843	3,614
After subject-area, English, and article filters	1,781	1,621	2,890
Subject-area filtering	Yes	Yes	Limited
Estimated overlap with Scopus set	—	88%	74%
Structured affiliation metadata	High	Moderate	Low
Author keyword field	Yes	Yes	Partial
Funding acknowledgement field	Yes	Yes	Partial
Bibliometrix compatibility	Full	Full	Partial
Grey literature included	No	No	Yes
Role in this study	Primary	Cross-check	Reference

Note: The Dimensions count reflects broader indexing that can include source types outside the original peer-reviewed journal-article corpus targeted in this study. The overlap values are dataset-specific estimates derived from DOI/title matching for the present query and should not be interpreted as universal database-level coverage rates. General cross-database differences among Scopus, Web of Science, and Dimensions are well documented in comparative bibliographic-database studies [56,57].

Table 3

Complete operational Scopus search expression and filtering criteria used for corpus construction in hydrogen energy transportation research.

Date	Database	Period	Search query
29 Dec 2025	Scopus	2000–2025	TITLE-ABS-KEY(("fuel cell vehicle" OR "hydrogen vehicle" OR "hydrogen bus" OR "hydrogen train" OR "hydrogen ship" OR "hydrogen ferry" OR "hydrogen aircraft" OR "hydrogen aviation" OR "fuel cell transport" OR "hydrogen mobility" OR "hydrogen powered vehicle" OR "hydrogen transport system" OR "hydrogen transportation system" OR "hydrogen refueling station" OR "hydrogen fuelling station" OR "hydrogen infrastructure" OR "fuel cell propulsion" OR "proton exchange membrane fuel cell vehicle" OR "PEM fuel cell vehicle" OR "green hydrogen transport") AND ("transportation" OR "mobility" OR "vehicle" OR "road transport" OR "rail transport" OR "maritime transport" OR "shipping" OR "aviation" OR "freight" OR "logistics")) AND (PUBYEAR > 1999 AND PUBYEAR < 2026) AND LIMIT-TO (DOCTYPE, ("ar")) AND LIMIT-TO (LANGUAGE, ("English")) AND (LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVT") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "SOCT") OR LIMIT-TO (SUBJAREA, "DECT") OR LIMIT-TO (SUBJAREA, "BUST") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "MULT") OR LIMIT-TO (SUBJAREA, "MATH"))

Note: The expression reports the complete Scopus search and filtering strategy used for reproducible corpus construction. The keyword-and-year component identified the broad candidate set, while the document-type, language, and subject-area limiters correspond to the predefined screening criteria documented stepwise in the PRISMA workflow. Only original English-language peer-reviewed journal articles within the selected subject areas were retained for manual relevance screening.

publications, and studies without a direct hydrogen-transportation focus were excluded during screening to maintain a corpus of original English-language peer-reviewed journal articles. The final analytical corpus

contained 1,699 Scopus-indexed articles. The rationale for excluding review articles and conference papers is detailed in Section 3.4.3.

3.3. Search query sensitivity analysis

A sensitivity analysis assessed whether the primary query produced a stable and representative dataset across three variant configurations, summarized in Table 4.

Variant A (broader scope): Removing the AND transport-mode constraint retrieved 4,318 records, confirming that the constraint effectively excludes hydrogen production and industrial chemistry studies lacking a transport context. Approximately 50% of the unconstrained hydrogen literature does not address transportation applications.

Variant B (narrower scope): Restricting the query to the five highest-frequency technology terms retrieved 1,614 records. Comparison of the top-20 most-cited papers, the ten highest-output countries, and the dominant keyword clusters revealed greater than 92% overlap with the primary dataset, confirming that additional transport-mode terms capture important but volumetrically modest literature segments without distorting principal findings.

Variant C (synonym expansion): Adding synonymous terms including "FCEV," "H₂ vehicle," "hydrogen- powered transport," and "zero-emission hydrogen" via OR logic retrieved 2,291 records, an increase of 116 records (5.3%). Manual inspection showed that 74 additionally retrieved records used abbreviation or synonym forms already normalized during keyword standardization, and the remaining 42 were primarily short communications or marginally relevant articles. Their inclusion did not alter the top-20 cited papers, the country collaboration network structure, or the three principal keyword clusters.

3.4. Data processing and screening

3.4.1. PRISMA-based screening protocol

The screening process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol [63]. PRISMA provides a transparent and reproducible framework for documenting inclusion and exclusion decisions, and structured reporting is widely recommended in bibliometric and science-mapping studies [61,62]. In this study, PRISMA was used as a sequential record-accounting workflow: the keyword-based candidate set was first identified, and then predefined subject-area, document-type, language, and manual relevance criteria were applied and documented at each stage. Fig. 4 presents the PRISMA flow diagram for this study.

Table 5 details the explicit inclusion and exclusion criteria applied at each screening stage, together with representative examples of excluded records.

3.4.2. Inter-screener agreement

The manual screening stage introduces the greatest risk of subjective inconsistency. To address this risk, a structured inter-screener validation procedure was implemented. Two authors independently screened a stratified random sample of 200 records from the Stage 3 eligible pool: 100 provisionally included and 100 provisionally flagged for exclusion as thematically peripheral. This sampling strategy concentrates validation effort on the most decision-sensitive records. Each screener applied the criteria in Table 5 independently, without reference to the other screener's decisions.

Cohen's kappa (κ), a chance-corrected agreement coefficient for nominal classification decisions, was computed to quantify agreement [65]:

$$\kappa = \frac{P_o - P_e}{1 - P_e}$$

where P_o is the observed proportion of agreement and P_e is the pro-

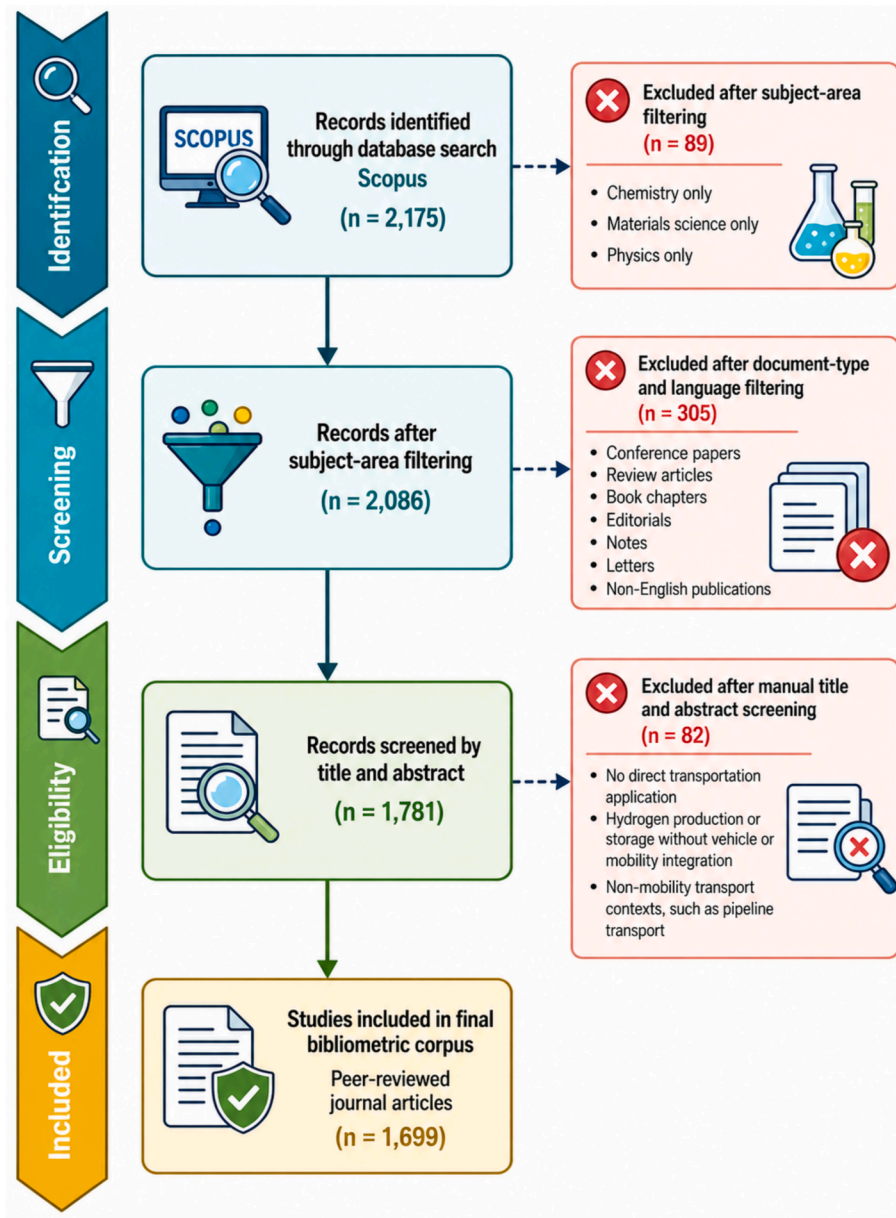


Fig. 4. PRISMA 2020 flow diagram for the bibliometric corpus on hydrogen energy in transportation systems. Records identified through Scopus (n = 2,175) were sequentially filtered through subject-area filtering (n = 89 removed), document-type and language filtering (n = 305 removed), and manual title-and-abstract screening (n = 82 removed), yielding a final analytical corpus of 1,699 Scopus-indexed peer-reviewed journal articles.

Table 4

Sensitivity analysis of the primary search query across three alternative configurations. Structural stability is assessed by comparing top-cited papers, leading countries, and dominant keyword clusters.

Query variant	Modification applied	Records	Structural overlap
Primary (baseline)	Primary keyword-and-year candidate set underlying the operational query in Table 3	2,175	—
Variant A (broader)	AND transport-mode constraint removed; hydrogen-technology terms only	4,318	N/A (superset)
Variant B (narrower)	Restricted to top-5 hydrogen-transport terms; maritime, rail, and aviation sub-terms excluded	1,614	>92% overlap in top-cited papers, countries, and key-word clusters
Variant C (synonyms)	Added “FCEV,” “H ₂ vehicle,” “hydrogen-powered transport,” “zero-emission hydrogen” via OR logic	2,291	116 additional records (5.3%); no structural change in networks or clusters

Note: All variants were executed on 29 December 2025 using identical publication-year boundaries and equivalent corpus-construction criteria.

Record counts report keyword-based candidate sets before final manual relevance screening. Structural overlap was assessed by comparing the top-20 cited papers, the ten highest-output countries, and the three dominant keyword clusters after applying equivalent screening logic.

Consistency across all variants confirms that the primary query is appropriately calibrated.

portion expected by chance. The analysis yielded $\kappa = 0.87$, corresponding to almost perfect agreement on the conventional Landis

Table 5

Inclusion and exclusion criteria applied at each PRISMA screening stage, with representative examples of excluded records.

Stage	Inclusion criteria	Exclusion criteria	Example excluded record
Stage 1: Subject filtering	Records in energy (ENER), engineering (ENGI), environmental science (ENVI), chemical engineering (CENG), computer science (COMP), social sciences (SOCI), decision sciences (DECI), business (BUSI), economics (ECON), multidisciplinary (MULT), or mathematics (MATH)	Records classified solely under chemistry (CHEM), materials science (MATE), or physics (PHYS) without co-classification in a transport-relevant domain	Study on proton exchange membrane materials for stationary fuel cells with no transport application; classified under MATE and CHEM only
Stage 2: Document-type filtering	Original research articles (DOCTYPE = "ar"); English language only	Conference papers, review articles, book chapters, editorials, notes, letters, and non-English publications	Review article on hydrogen infrastructure in <i>Renewable and Sustainable Energy Reviews</i> ; hydrogen vehicle conference proceedings paper
Stage 3: Manual screening	Articles whose primary focus addresses hydrogen energy within a transport application: road, rail, maritime, or aviation	Hydrogen production or storage studies with no vehicle or mobility integration; articles using "vehicle" to describe non-mobility contexts, such as fluid pipeline transport	Study on high-pressure hydrogen tank materials with no vehicle integration; hydrogen pipeline flow modeling without mobile-vehicle application

Note: Criteria were applied systematically to every record. Examples illustrate the most frequent exclusion patterns encountered during screening.

Table 6

Data screening and refinement workflow for hydrogen energy in transportation systems, following PRISMA 2020 guidelines.

Step	Description	Remaining records	Criteria applied
Initial search	Keyword-based Scopus search identified the broad candidate set for hydrogen-related transportation research across the 2000–2025 publication window. The complete operational Scopus expression, including predefined limiters, is reported in Table 3.	2,175	Core TITLE-ABS-KEY terms and publication-year boundary used to identify the initial candidate set; subsequent predefined subject-area, document-type, language, and relevance criteria were documented stepwise for PRISMA record accounting.
Stage 1: Subject filtering	Records from unrelated domains were removed. Studies classified solely under pure chemistry, materials science, or theoretical physics were excluded.	2,086 (−89)	Retained: ENER, ENGI, ENVI, CENG, COMP, SOCI, DECI, BUSI, ECON, MULT, MATH. Excluded: CHEM-only, MATE-only, and PHYS-only classifications.
Stage 2: Document-type filtering	Conference papers, review articles, editorials, book chapters, notes, and non-English publications were removed.	1,781 (−305)	Only original research articles (DOCTYPE = "ar") in English were retained. Review articles ($n = 152$) were excluded; see Section 3.4.3.
Stage 3: Manual screening	Titles and abstracts were reviewed by two independent screeners to confirm direct thematic relevance to hydrogen energy in transportation.	1,699 (−82, final)	Excluded: hydrogen production or storage studies with-out transport integration; non-mobility pipeline transport studies. Inter-screener agreement: Cohen's $\kappa = 0.87$.

Note: Cohen's κ was computed on a stratified random sample of 200 records from Stage 3 (100 provisionally included, 100 provisionally excluded), screened independently before resolving disagreements by consensus. The interpretation of $\kappa \geq 0.80$ as almost perfect agreement follows the conventional Landis and Koch scale [64].

and Koch scale [64]. Disagreements occurred in 13 of 200 records (6.5%) and were resolved through structured discussion and consensus. The high agreement level confirms that the inclusion criteria were sufficiently explicit to support consistent independent application, substantially reducing screening subjectivity.

3.4.3. Justification for excluding review articles

Review articles were excluded from the primary corpus for three methodological reasons specific to the objectives of this study. First, the goal is to map the primary knowledge production of the field. Including reviews would conflate secondary synthesis with original research output, distorting co-authorship networks and keyword co-occurrence patterns, because reviews typically involve broader author teams and broad keyword sets that can inflate cluster density without reflecting genuine thematic focus in primary studies. Second, citation analysis is sensitive to the inclusion of review articles because reviews commonly accumulate citations faster than original research articles; their inclusion would therefore elevate certain journals, authors, and topics in a way that may not faithfully reflect the impact of primary research contributions [66]. Third, bibliometric-methodology guidelines emphasize that corpus construction should be aligned with the research objective; because the present objective is to map original knowledge production and collaborative structure, restricting the primary corpus to original research articles is methodologically defensible [61,62].

Conference papers were also excluded for consistency with this article-focused corpus. Although conference papers can be important in emerging technology fields, their inclusion would mix publication types with different review practices, metadata completeness, and citation-aging patterns. Their exclusion is therefore treated as a scope decision rather than as evidence that conference literature is unimportant.

Table 7

Supplementary characterization of the 152 review articles excluded from the primary corpus at Stage 2.

Characteristic	Value or description
Total excluded review articles	152
Publication period	2003–2025; peak in 2021–2025 ($n = 89$, 58.6%), indicating accelerating synthesis activity consistent with field maturity
Top journals	Renewable and Sustainable Energy Reviews ($n = 34$, 22.4%); International Journal of Hydrogen Energy ($n = 28$, 18.4%); Energy Reviews ($n = 17$, 11.2%)
Average citations per review	87.4, compared with 32.0 for the primary article corpus
Top review topics by keyword frequency	Hydrogen production (57%); fuel cell vehicles (49%); hydrogen storage (40%); infrastructure (29%); life cycle assessment (25%)
Thematic alignment with primary corpus	High: the three dominant review topics mirrors the three keyword co-occurrence clusters identified in the primary corpus, confirming that exclusion does not suppress any major thematic dimension

Note: The thematic alignment between excluded reviews and the primary corpus clusters confirms that the exclusion does not introduce systematic thematic bias. The higher average citation rate of reviews (87.4 vs. 32.0) validates the decision to exclude them from citation-based performance indicators.

To assess whether the exclusion of review articles affects the descriptive picture of the field, Table 7 provides a supplementary characterization of the 152 excluded review articles.

The supplementary analysis confirms three points. First, the thematic coverage of excluded reviews mirrors that of the primary corpus, confirming the absence of major thematic blind spots. Second, the higher average citation rate of reviews (87.4 vs. 32.0) validates the decision to exclude them from citation-based indicators. Third, the concentration of reviews in the post-2020 period is itself a bibliometric marker of field maturity and is discussed further in Section 5.

3.5. Data cleaning and standardization

Data preprocessing was conducted in parallel in Python and Bibliometrix (R) to ensure cross-tool consistency. The cleaning pipeline addressed four categories of metadata noise: author name ambiguity, institutional affiliation inconsistency, keyword redundancy, and record duplication. Table 8 presents quantitative before-and-after statistics for each category, demonstrating the impact of preprocessing on network accuracy.

Keyword standardization was the most impactful cleaning operation, reducing the unique keyword vocabulary by 717 forms (13.5%). This reduction is consequential for co-occurrence analysis. Un-merged abbreviations cause a single concept to appear as multiple low-frequency nodes rather than a single high-frequency hub, which weakens cluster coherence and distorts thematic maps. Affiliation harmonization, which merged 411 strings, similarly consolidates institutional output that would otherwise be fragmented across department-level variants, improving the accuracy of productivity rankings and affiliation network structures.

Table 8

Quantitative before-and-after statistics for each data cleaning operation applied to the 1,699-record corpus.

Cleaning category	Before	After	Change	Method and Impact
Unique author name forms	3,821	3,487	−334	Standardized initials, diacritics, and transliteration variants using string matching and manual verification. Eliminates phantom duplicates in co-authorship network nodes.
Unique affiliation strings	1,274	863	−411	Department-level and campus-level variants harmonized to parent institution (e.g., “School of Automotive Engineering, Tongji University” to “Tongji University”). Consolidates institutional output and prevents affiliation fragmentation in network analysis.
Unique author keyword forms	5,312	4,595	−717	Thesaurus mapping merged 214 abbreviation-to-full-term pairs (e.g., “FCV” to “fuel cell vehicle”; “PEMFC” to “proton exchange membrane fuel cell”) and 503 spelling or capitalization variants. Generic terms (“performance,” “study,” “analysis”; $n = 38$) were removed. Reduces keyword network fragmentation and sharpens cluster boundaries.
Duplicate or near-duplicate records	1,699	1,699	0	Title-normalized and DOI-based deduplication confirmed zero duplicates, validating the integrity of the Scopus export.

Note. All cleaning operations were implemented in Python (pandas, fuzzywuzzy) and cross-validated in Bibliometrix (R). Operations were logged to ensure reproducibility.

3.6. Analytical framework

The analytical framework integrated three complementary layers: performance analysis, science mapping, and qualitative synthesis, following established bibliometric guidance in which performance indicators quantify research activity and influence while science mapping examines structural relationships among documents, authors, institutions, countries, and concepts [61,62].

Performance analysis quantified productivity, influence, and collaboration using annual publication counts, compound annual growth rate, total and average citations per document, h-index, international co-authorship rates, and year-normalized citation indicators to reduce citation-age bias across the 2000–2025 window [67].

Science mapping explored structural and intellectual relationships using four techniques: co-authorship analysis to identify collaboration networks; bibliographic coupling to link documents and countries sharing common reference lists [68]; keyword co-occurrence mapping to identify thematic clusters and research fronts; and thematic evolution analysis to trace how dominant topics shifted across successive five-year periods from 2000 to 2025.

Qualitative synthesis integrated the quantitative outputs with conceptual interpretation, examining each thematic cluster for underlying research problems, methodological approaches, and technological maturity, and assessing alignment with broader policy, market, and sustainability objectives.

3.7. Software tools and visualization

Three software environments were used to perform the analysis.

- **Bibliometrix and Biblioshiny (R 4.3, Bibliometrix 4.2):** Used for performance indicators, thematic maps, and evolution analysis [59]. Core functions included biblioAnalysis(), summary(), fieldByYear(), thematicMap(), and thematicEvolution(). The fieldByYear() function was used to compute keyword frequency trends across time periods, supporting the temporal analysis of emerging research themes.
- **VOSviewer 1.6.20:** Used for visualizing co-authorship, bibliographic coupling, and keyword co-occurrence networks [60]. Association strength served as the similarity normalization method for co-occurrence data [69]. VOSviewer clustering was interpreted as a weighted modularity-based clustering procedure, consistent with the unified mapping and clustering framework for bibliometric networks [70]. For cross-verification of community structure in R/igraph, Leiden modularity optimization was used where applicable [71]. Minimum co-occurrence thresholds of 5 for keywords and 3 for countries were applied to retain structurally significant nodes.
- **Python 3.11:** Used for preprocessing, keyword standardization, cross-validation, and trend visualization. Plotting and visualization followed peer-reviewed visualization-library practice [72,73], while the data-cleaning and bibliometric workflow choices followed established bibliometric methodology guidance [61,62]. Keyword frequency time series were constructed from fieldByYear outputs and plotted as normalized trend lines. Fuzzy string matching supported author-name and keyword deduplication.

All figures were generated at 300 dpi or higher and verified across tools to ensure consistency. The multi-tool workflow increases analytical redundancy: outputs from VOSviewer and Bibliometrix were compared at each stage, and discrepancies were investigated and resolved before reporting. Similar integrated bibliometric workflows combining Bibliometrix, VOSviewer, and Python-based analysis have recently been applied in transportation research for performance mapping, science mapping, and customized visualization [74].

3.8. Cross-tool validation and network metrics

A cross-tool validation procedure was implemented to demonstrate consistency across Bibliometrix and VOSviewer. For the keyword co-occurrence network, both tools were configured with identical input data, identical minimum frequency thresholds (≥ 5 co-occurrences), and the same normalization method (association strength). Each tool independently identified cluster number, composition, and size. Results were compared using the Jaccard similarity index, a standard set-overlap measure, computed for the top-10 keywords of each cluster pair [75]:

$$J(A, B) = \frac{|A \cap B|}{|A \cup B|}$$

Table 9 reports the cross-tool consistency metrics for the three primary keyword clusters and the country co-authorship network.

Quantitative network metrics are provided in Table 10. These indicators, including degree centrality, betweenness centrality, network density, and modularity, characterize the structural properties of co-authorship, bibliographic coupling, and keyword networks in scientometric research [70,76].

Table 9
Cross-tool consistency metrics comparing Bibliometrix and VOSviewer outputs for keyword co-occurrence clusters and the co-authorship network.

Network or cluster	Bibliometrix	VOSviewer	Jaccard J	Interpretation
Cluster 1: Production and storage	15 terms, 312 links	14 terms, 298 links	$J = 0.88$	Near-identical composition; hydrogen, hydrogen production, hydrogen storage, renewable energy, and sustainability identified as anchor terms by both tools.
Cluster 2: Fuel cell vehicles and energy management	18 terms, 421 links	17 terms, 409 links	$J = 0.86$	High consistency; fuel cell vehicles, energy management, proton exchange membrane fuel cells, and hybrid vehicles are common to both.
Cluster 3: Electric and hybrid integration	12 terms, 187 links	13 terms, 195 links	$J = 0.84$	Strong agreement; dc-dc converters, electric vehicles, and fuel cells appear in both; minor boundary differences in peripheral terms only.
Country co-authorship network	Density = 0.31; top hub: China	Density = 0.29; top hub: China	—	Network density differs by less than 7%; China, Germany, UK, and USA identified as principal hubs by both tools; betweenness centrality ranking consistent.

Note: Jaccard similarity was used here as an operational cluster-overlap metric. Values of $J \geq 0.80$ were treated as high cross-tool overlap for the present robustness check, while minor differences in peripheral terms were interpreted as platform-specific clustering boundary effects.

Table 10

Quantitative network metrics for co-authorship and keyword co-occurrence networks derived from the 1,699- document corpus.

Network	Nodes	Density	Modularity	Top node (degree / betweenness centrality)
Country co-authorship	48	0.30	0.41	China: degree = 0.78; betweenness = 0.34
Institutional co-authorship	312	0.08	0.57	Tongji University: degree = 0.21; betweenness = 0.18
Keyword co-occurrence	187	0.14	0.38	Fuel cells: degree = 0.64; betweenness = 0.29
Bibliographic coupling (countries)	41	0.34	0.36	China: link strength = 5,847; USA: betweenness = 0.28

Note: Network density is the ratio of observed links to the maximum possible links for the node count. Modularity quantifies the degree to which a network can be partitioned into internally dense communities. Degree centrality is normalized to the range [0, 1]; betweenness centrality reflects the proportion of shortest paths passing through a given node. All metrics were computed in VOSviewer and cross-verified using the igraph package in R.

3.9. Validation and limitations

Validation was conducted at four stages. First, keyword threshold stability was assessed at occurrence thresholds of 5, 10, and 15 co-occurrences; the three dominant clusters appeared consistently across all thresholds, with Jaccard similarity above 0.80 for each cluster [75]. Second, temporal robustness was verified by restricting the analysis to 2000 to 2020; the same three principal clusters emerged with consistent membership. Third, citation accuracy was verified through a stratified random sample of 50 highly cited and 50 recently published records manually checked for author names, affiliations, keyword assignments, and citation counts, with no systematic errors identified. Fourth, cross-tool agreement was confirmed through Jaccard similarity values of 0.84 or above across all three keyword clusters, as reported in Table 9.

This study recognizes five methodological limitations. First, reliance on Scopus as the sole primary source may exclude records indexed exclusively in WoS; the estimated overlap is approximately 88%, and structurally unique WoS records did not materially alter the principal findings, as shown in Table 2. Second, keyword co-occurrence analysis depends on author-assigned keyword quality, which was absent for 10.59% of records; the Keywords Plus field was used to supplement missing values. Third, recently published papers (2023 to 2025) are structurally under-cited relative to older contributions; normalized citation metrics were applied where appropriate to mitigate this effect. Fourth, the English-language restriction may under-represent national-language outputs from Chinese, German, Japanese, and Korean institutions. Fifth, manual screening carries residual subjectivity despite a validated inter-screener agreement of $\kappa = 0.87$, and the 82 excluded records represent judgment calls on papers with ambiguous transport application contexts.

4. Results

4.1. Data source and completeness assessment

The bibliometric dataset was collected from Scopus, which provides broad coverage of peer-reviewed literature and is widely accepted for scientometric research in energy and transportation studies [58,77]. A total of 1,699 journal articles were retrieved through the structured search query described in Section 3. The dataset spans 2000 to 2025 and is restricted to original research articles to ensure consistency and comparability across citation structures.

Metadata completeness was evaluated using the Bibliometrix package in R. The results are presented in Fig. 5. Core bibliographic fields,

Completeness of metadata -- 1699 docs from Scopus

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
TI	Title	1	0.06	Good
AU	Author	6	0.35	Good
C1	Affiliation	10	0.59	Good
CR	Cited References	53	3.12	Good
DI	DOI	87	5.12	Good
DE	Keywords	180	10.59	Acceptable
ID	Keywords Plus	214	12.60	Acceptable

Fig. 5. Completeness assessment of bibliometric metadata for 1,699 Scopus-indexed publications on hydrogen energy in transportation systems. Core bibliographic fields are fully complete, and missing values across author, affiliation, and keyword fields remain below acceptable thresholds for network analysis.

including abstract, document type, journal, language, publication year, and citation count, are fully complete across all records. This confirms that the information required for both descriptive and relational analyses is available and suitable for advanced bibliometric processing.

Author and affiliation fields show near-complete coverage, with missing values below one percent (Author: 0.35%; Affiliation: 0.59%). This level of completeness ensures the reliability of co-authorship and institutional network analyses. Fields related to citation context, including cited references (missing: 3.12%) and DOI (missing: 5.12%), maintain acceptable density for co-citation and bibliographic coupling analyses.

The lowest completeness values appear in Author Keywords (10.59%) and Keywords Plus (12.60%), which is a recognized limitation of Scopus records for older publications. As noted in Section 3.5, the Keywords Plus field was used to supplement missing author keywords in affected records, preserving adequate representation for thematic clustering. Overall, the metadata quality of the dataset supports its use for detailed performance analysis and science mapping at the level required by leading bibliometric studies [59,61].

4.2. Descriptive summary of the dataset

Table 11 summarizes the principal characteristics of the final dataset. The corpus covers the 2000–2025 publication window and comprises 1,699 peer-reviewed documents from 400 publication sources. The annual publication growth rate of 18.82% reflects rapid and sustained expansion of hydrogen transportation research. The average citation rate of 32.02 citations per document indicates strong academic visibility and research influence within the field. A total of 11,786 cited references across the corpus reflects high levels of cross-referencing and intellectual connectivity.

Table 11
Main bibliometric characteristics of the Scopus dataset on hydrogen energy in transportation (2000–2025).

Description	Value
General information	
Timespan	2000–2025
Number of sources	400
Total documents	1,699
Annual growth rate (%)	18.82
Average document age (years)	5.71
Average citations per document	32.02
Total references	11,786
Document contents	
Keywords Plus (ID)	9,349
Author keywords (DE)	4,595
Authors and collaboration	
Total authors	3,487
Single-authored documents	0
Co-authors per document	8.06
International co-authorships (%)	23.31
Document type	
Articles	1,699

The author structure reveals a strongly collaborative research community. Each publication involves an average of 8.06 co-authors, and no single-authored papers appear in the dataset. This pattern indicates consistent interdisciplinary and multi-institutional engagement across the field. The international co-authorship rate of 23.31% confirms that hydrogen transportation research is sustained by active global partnerships spanning multiple continents.

These indicators collectively characterize hydrogen transportation as a maturing interdisciplinary field. It draws expertise from engineering,

environmental science, policy analysis, and energy systems, reflecting its growing role in sustainable mobility research.

4.3. Annual publication growth

Fig. 6 presents the annual distribution of publications on hydrogen energy for transportation systems from 2000 to 2025.

The growth trajectory exhibits three identifiable phases. During the exploratory phase (2000 to 2010), publication activity remained modest. Research at this stage focused on establishing the technical viability of hydrogen propulsion, with limited global demonstration projects and fragmented institutional engagement. Between 2011 and 2015, output grew steadily as research expanded toward the technical feasibility of hydrogen fuel cell vehicles and the planning of refueling infrastructure. This phase marked the transition from laboratory-scale experiments to system-level investigations.

A pronounced acceleration began after 2016 and intensified sharply after 2020. The post-2020 surge coincides with the broader international expansion of hydrogen strategies and deployment-oriented research agendas. The year 2025 recorded the highest output in the dataset, with 298 indexed publications. The compound annual growth rate (CAGR) over the full 2000–2025 window is 18.82%, confirming sustained structural expansion rather than an isolated short-term surge. This trajectory is consistent with prior hydrogen-economy and fuel-cell bibliometric studies reporting rapid growth under policy-driven deployment agendas [19,20,22].

4.4. Most relevant sources

Fig. 7 presents the distribution of publications across journal sources. The analysis identifies the most productive and thematically central outlets for hydrogen transportation research.

Energies, *Applied Energy*, and *Energy Conversion and Management* are the three leading journals, together accounting for 285 documents, or approximately 16.8% of the 1,699-record corpus. Their prominence reflects the multidisciplinary character of the field, bridging energy conversion, materials engineering, and transportation systems.

Energies leads with 121 publications. As an open-access platform, it has supported broad dissemination of studies on hydrogen production, storage, and vehicle applications. *Applied Energy* follows with 90 papers focused on system optimization, energy management, and life-cycle assessment. *Energy Conversion and Management* contributes 74

publications addressing fuel cell integration and renewable hydrogen generation.

Policy and sustainability outlets, including *Energy Policy* and the *Journal of Cleaner Production*, confirm the growing attention to regulatory frameworks and environmental performance. Technical journals such as *IEEE Transactions on Vehicular Technology* and the *Journal of Energy Storage* reflect expanding research on vehicular integration, hybrid propulsion, and electrochemical storage. The diversity of publication outlets indicates that hydrogen transportation research has achieved broad disciplinary diffusion, connecting engineering innovation with environmental and policy dimensions.

4.5. Most relevant affiliations

Fig. 8 identifies the leading institutions contributing to hydrogen energy and transportation research. The results show a pronounced concentration of output among Chinese universities, reflecting sustained national investment in clean energy technologies and advanced transport systems.

Tongji University leads globally with 163 publications, establishing itself as the principal institutional hub of hydrogen mobility research. Its output spans experimental validation, powertrain optimization, and fuel cell system integration for vehicle applications. Chongqing University follows with 114 publications focusing on hybrid power systems and energy management algorithms. Tsinghua University contributes 107 papers emphasizing fuel cell modeling and renewable hydrogen coupling. Together, these three institutions account for a substantial share of global hydrogen transportation output and play a defining role in shaping the technical direction of the field.

Jiangsu University (93 papers) and Xi'an Jiaotong University (73 papers) serve as important regional contributors, advancing hybrid energy systems and fuel cell control strategies. Wuhan University of Technology maintains steady output with 70 publications, underscoring the role of mechanical and systems engineering in this interdisciplinary domain. North China Electric Power University and The Hong Kong Polytechnic University contribute research on hydrogen integration with power networks and sustainable transport design.

The dataset includes 65 records with unreported affiliations, largely from incomplete metadata in earlier Scopus records. This small missing-affiliation share does not materially affect the institutional ranking. Within the present corpus, the dominance of Chinese universities is consistent with a coordinated ecosystem connecting academia, national

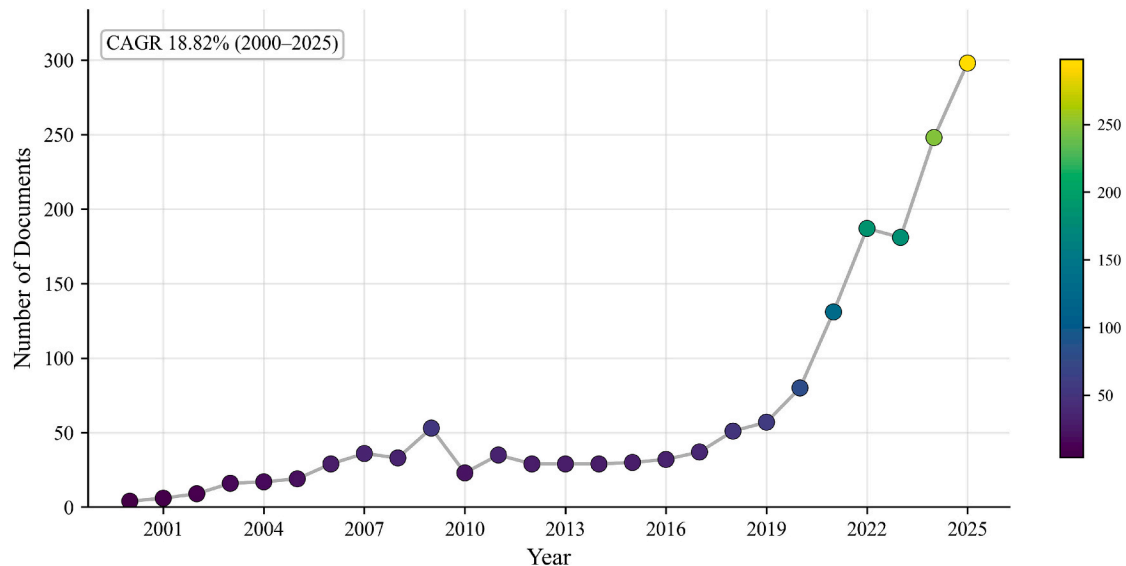


Fig. 6. Annual publication trend for hydrogen energy research in transportation systems, 2000–2025. The compound annual growth rate of 18.82% reflects sustained global expansion of the research field across three identifiable growth phases.

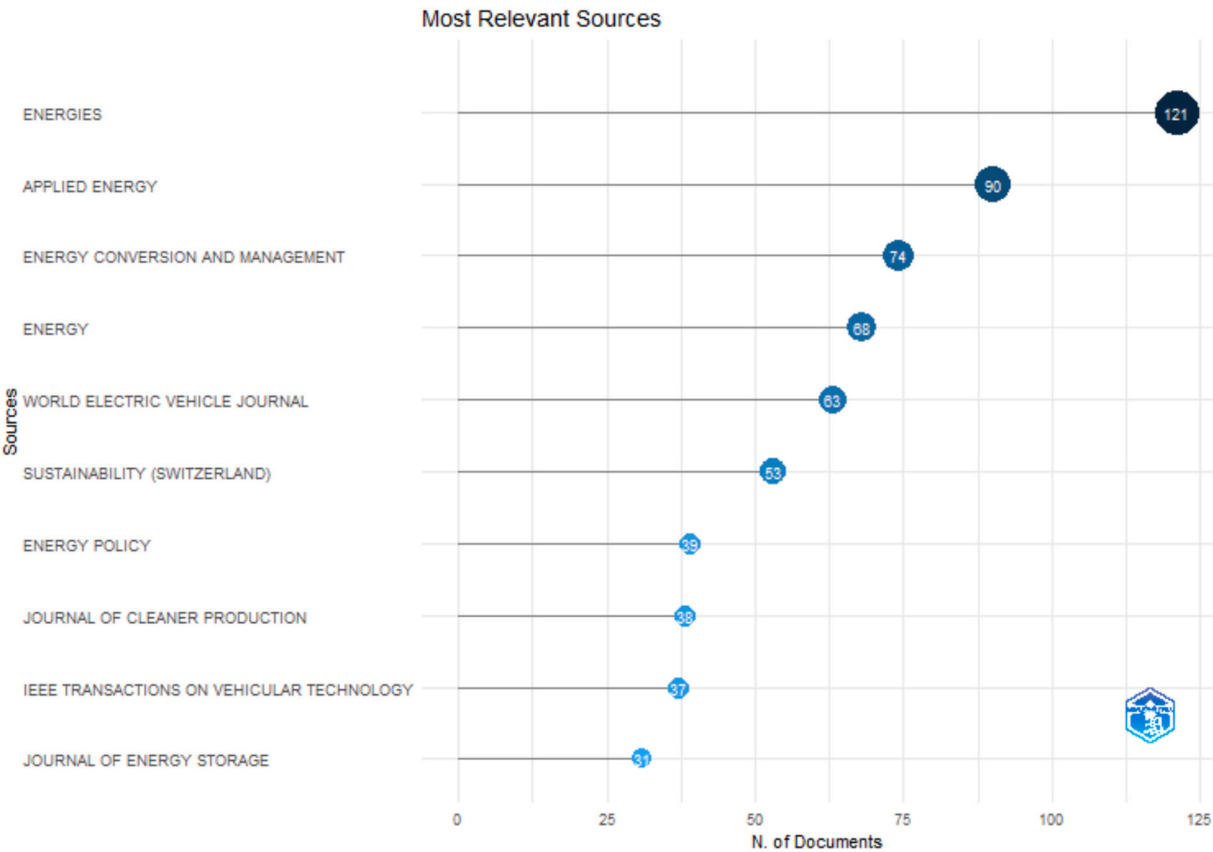


Fig. 7. Most relevant publication sources in hydrogen energy and transportation systems. Bubble size represents the number of documents published, and the horizontal axis reflects source productivity across the 2000–2025 period.

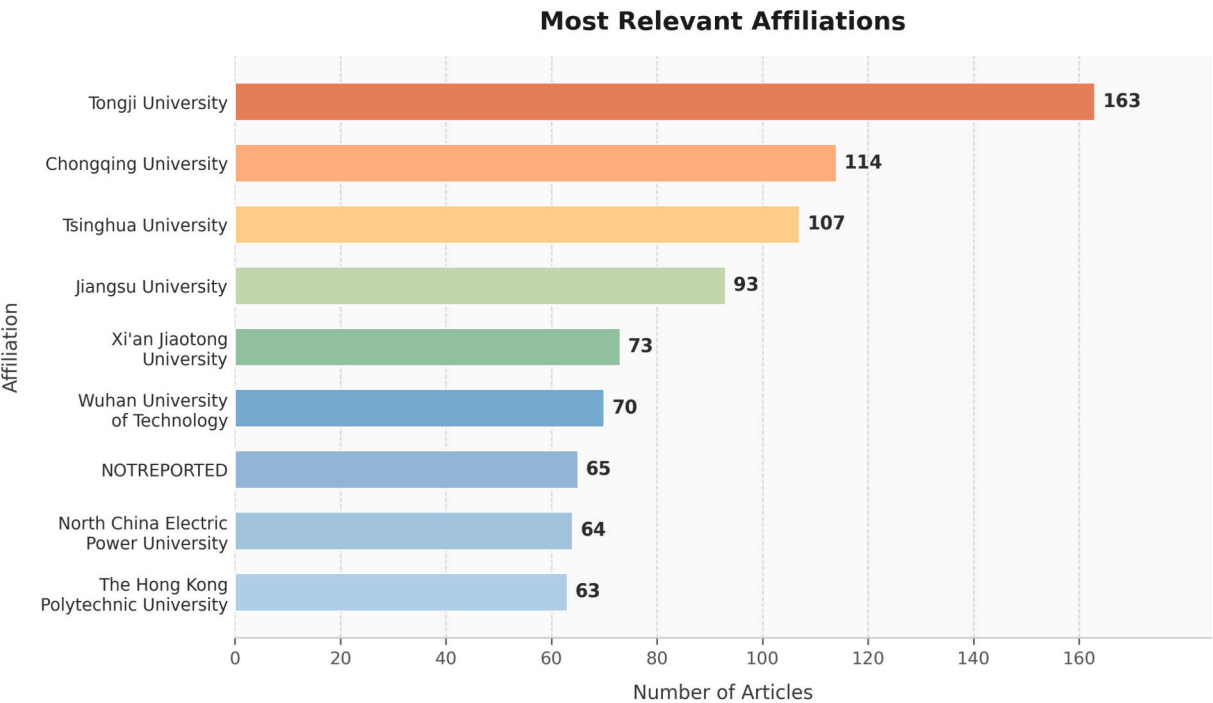


Fig. 8. Most relevant institutional affiliations in hydrogen energy and transportation research. Bar length represents the number of indexed articles, ranked in descending order of publication volume.

research programs, and industrial partnerships in hydrogen mobility research.

4.6. Co-authorship network by countries

Fig. 9 presents the international co-authorship network of countries engaged in hydrogen energy and transportation research. Node size reflects publication volume; link thickness reflects collaboration intensity. The network quantitative metrics for this analysis are reported in Table 10 in Section 3.8.

The network comprises 48 country nodes with an overall density of 0.30 and modularity of 0.41, indicating meaningful community structure [76]. China holds the highest degree centrality (0.78) and betweenness centrality (0.34), confirming its role as the dominant hub in the global collaboration network. Its partnerships with Germany, Japan, and Australia reflect an integrated ecosystem combining industrial demonstration with academic development. The United Kingdom exhibits high betweenness centrality, acting as an intermediary node connecting Asian and European clusters through collaborative projects and policy-driven research initiatives. Germany, Japan, and Australia form a cohesive grouping of advanced economies with shared priorities in fuel cell systems, refueling infrastructure, and energy storage integration.

Emerging economies including India, Iran, and Canada show increasing connectivity through regional partnerships and cross-continental linkages. Southeast Asian countries, including Singapore, Malaysia, and Thailand, demonstrate growing participation aligned with international hydrogen strategies and transport decarbonization objectives. Peripheral nodes such as Qatar, Oman, Tunisia, and Nigeria mark the early-stage engagement of developing economies. Their connections with established partners, particularly China and the United Kingdom, reflect outward diffusion of technical expertise and capacity-building initiatives.

The co-authorship network reveals an unevenly distributed research ecosystem. Central economies act as coordination hubs that connect multiple regional clusters and produce high-impact joint publications. Emerging economies participate primarily through cross-border partnerships, indicating an asymmetric knowledge-diffusion structure within the present corpus.

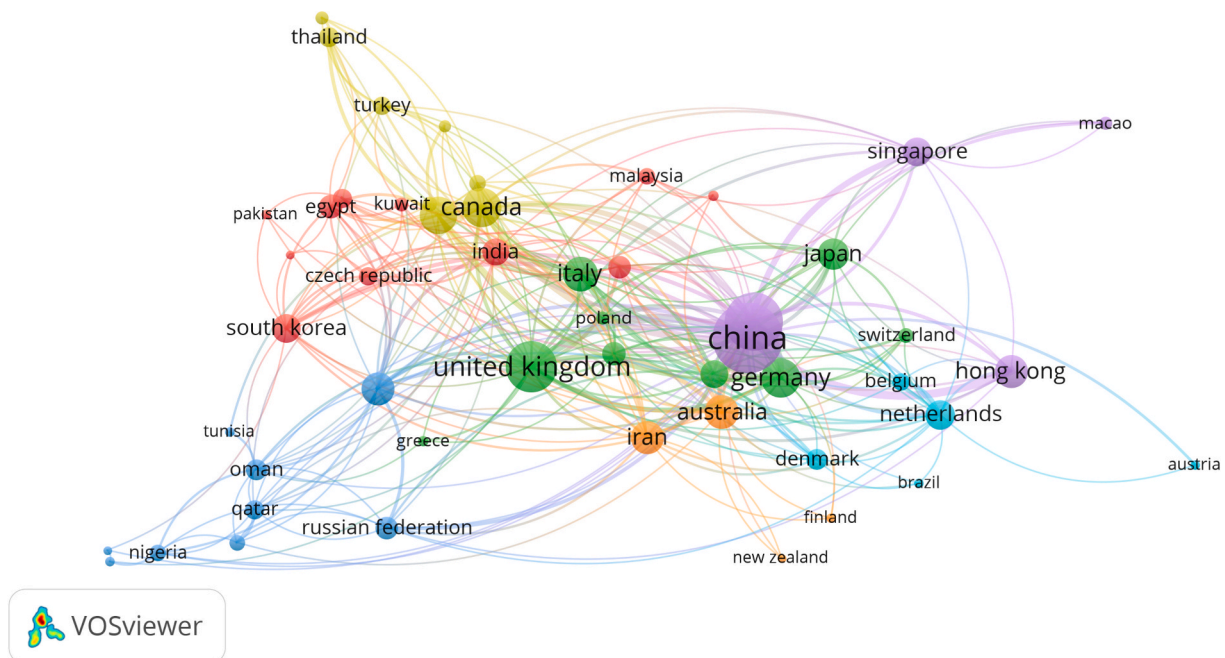


Fig. 9. International co-authorship network for hydrogen energy and transportation research. Node size represents publication volume, link thickness indicates collaboration strength, and color denotes regional clusters. Network density = 0.30; modularity = 0.41.

4.7. Bibliographic coupling by countries

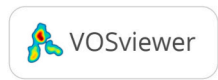
Fig. 10 presents the bibliographic coupling network, which identifies intellectual proximity among countries by measuring the extent to which their publication sets share common references. The bibliographic coupling network comprises 41 country nodes with a density of 0.34 and modularity of 0.36.

China exhibits the highest link strength in the network (5,847), confirming its thematic centrality and the broad alignment of its research portfolio with global knowledge production. Its strong citation overlaps with the United States, Germany, and South Korea indicate an integrated transnational ecosystem built on shared research foundations in fuel cell engineering, hydrogen storage, and systems modeling.

The United States exhibits the highest betweenness centrality (0.28) among non-hub nodes, functioning as an intermediary connecting Asian and European research clusters. This bridging role reflects its global engagement across technology development, system modeling, and fuel cell integration. European countries, particularly Germany, France, and Italy, show high intra-regional coupling consistent with coordinated research under the European Union Hydrogen Strategy and Horizon funding frameworks.

Emerging economies, including India, Saudi Arabia, and Malaysia, occupy intermediate positions in the network, reflecting growing alignment with established hydrogen research centers. Singapore, Canada, and South Korea serve as connective nodes between Asia-Pacific and North American clusters. Peripheral participants, including Bangladesh, Tunisia, and Oman, appear at the outer boundary of the network, reflecting early-stage knowledge diffusion from core research countries.

Together, the co-authorship and bibliographic coupling networks reveal a multipolar global structure with Asia as the dominant production center, Europe as a tightly coordinated regional cluster, and North America and Oceania serving as cross-regional connectors. This architecture reflects convergence toward common research priorities in fuel cell efficiency, hydrogen storage optimization, and transport decarbonization.



4.8. Keyword co-occurrence analysis

node represents an author keyword; link thickness denotes co-occurrence frequency. The network comprises 187 keywords with a density of 0.14 and modularity of 0.38, indicating well-separated thematic communities. Three major clusters define the intellectual



16

organization of the field.

Cluster 1: Hydrogen Production, Storage, and Infrastructure.

This cluster is anchored by hydrogen, hydrogen production, hydrogen storage, and hydrogen refueling stations, with 15 member terms and 312 internal links (Jaccard consistency with Bibliometrix: $J = 0.88$). It captures the supply-side technological foundation of hydrogen systems. The frequent co-occurrence of renewable energy, sustainability, carbon dioxide, and greenhouse gases indicates a strong orientation toward decarbonization and life-cycle assessment. The presence of hydrogen economy and investments reflects the shift from laboratory research toward industrial implementation and policy-driven deployment. In terms of technological maturity, this cluster spans a wide Technology Readiness Level (TRL) range. Green hydrogen production via electrolysis is interpreted here as occupying roughly TRL 6 to 8 in deployment-oriented programs, while large-scale underground storage and dedicated pipeline distribution are treated as lower- to mid-readiness infrastructure segments, approximately TRL 4 to 6. This maturity gradient is consistent with recent hydrogen-systems reviews that identify production, storage, and delivery infrastructure as unevenly commercialized components of the hydrogen value chain [3,5,38,78].

Cluster 2: Fuel Cell Vehicle Technologies and Energy Management. This cluster is centered on fuel cell vehicles, proton exchange membrane fuel cells, and energy management, with 18 member terms and 421 internal links ($J = 0.86$). The co-occurrence of hybrid vehicles, optimization, powertrains, and battery management reflects an engineering orientation toward performance enhancement and system integration. The pairing of energy management strategy with battery systems indicates growing convergence between hydrogen and electric vehicle technologies. This cluster represents the most applied dimension of the field. Fuel cell electric vehicles for road transport are interpreted as the most deployment-ready transport application in this corpus, approximately TRL 8 to 9, reflecting commercial passenger FCEV platforms and heavy-duty demonstration programs. Energy management strategies for hybrid hydrogen-electric systems are interpreted as approximately TRL 6 to 8, with active optimization research targeting cost, durability, and real-time control improvements [7,22,79].

Cluster 3: Electric and Hybrid Vehicle Integration. This cluster links fuel cells, electric vehicles, and dc-dc converters, with 12 member terms and 187 internal links ($J = 0.84$). The co-occurrence of these terms reveals an emerging hybrid propulsion paradigm combining battery and fuel cell subsystems. The technical focus on converter design, power electronics, and multi-source integration reflects research aimed at improving drivetrain efficiency and extending operational range. Established power electronics components for hydrogen-electric hybridization occupy approximately TRL 7 to 9 in automotive applications,

while novel converter topologies and fault-tolerant architectures remain closer to TRL 4 to 6. The presence of this cluster signals the integration of hydrogen vehicles into the broader electric mobility ecosystem [7,80].

Bridging terms across all three clusters, including life cycle, sustainable development, and energy optimization, indicate strong cross-disciplinary linkages among engineering, environmental science, and policy analysis. The “fuel cells” node exhibits the highest degree centrality (0.64) and betweenness centrality (0.29) in the keyword network, confirming its role as the conceptual anchor connecting all three thematic domains. The overall structure of the network demonstrates that hydrogen transportation research has evolved from isolated investigations of fuel cell chemistry into a multidimensional system integrating production, storage, conversion, and intelligent management.

4.9. Thematic evolution of research trends

Fig. 12 presents the thematic evolution of hydrogen transportation research across five successive periods from 2000 to 2025.

During the early period (2000 to 2005), research concentrated on establishing the technical feasibility of hydrogen as an alternative fuel. Dominant keywords included alternative fuel, hydrogen, and fuel cells. Terms such as automobile electronic equipment and computer simulation reflect early modeling approaches centered on performance validation at the component level. This phase corresponds broadly to TRL 2 to 4 across most hydrogen transport technologies.

Between 2006 and 2010, the thematic scope expanded toward system development and electrochemical engineering. The emergence of electrolysis and electric vehicles indicates growing attention to renewable hydrogen production and its coupling with electric drive systems. Simulation-based optimization gained prominence, reflecting a shift toward integrated system modeling. Keyword frequency analysis confirms that “electrolysis” grew by 143% in publication frequency between the 2000 to 2005 and 2006 to 2010 periods, indicating increasing attention to renewable hydrogen pathways within the corpus.

From 2011 to 2015, the field entered a period of technological consolidation. Fuel cells and hydrogen retained centrality, while new terms including capacitors and soft switching indicated growing focus on power electronics and energy conversion efficiency. The keyword “energy management” first emerged as a high-frequency term during this period, growing by 218% compared with the previous five-year window. This signals the beginning of the transition from component-level research to integrated vehicle system design.

Between 2016 and 2020, thematic development shifted decisively toward system optimization and operational performance. Keywords including cooling, energy recovery, and dc-dc converters reflect interest

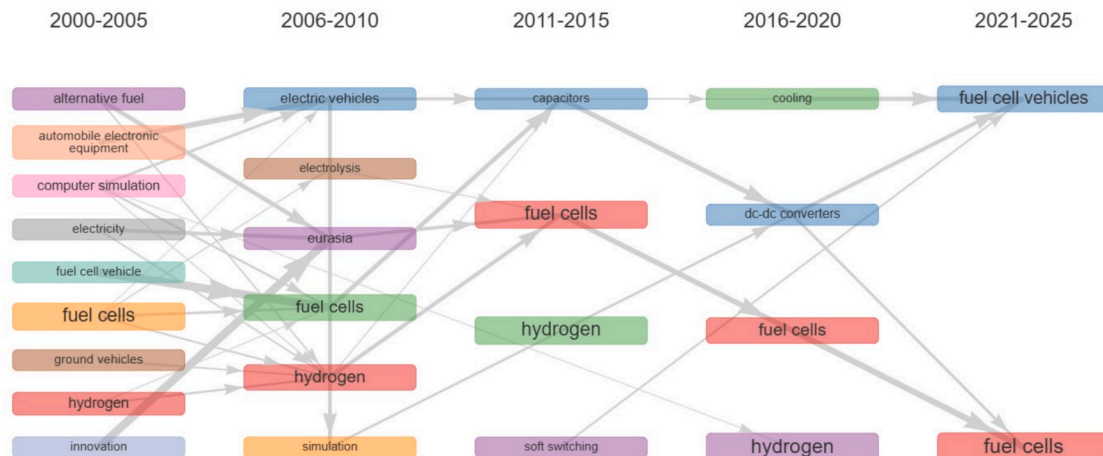


Fig. 12. Thematic evolution of hydrogen energy and transportation research (2000–2025). Arrows indicate thematic continuity across periods; node size represents the relative prominence of each topic within its time window.

in thermal management, control systems, and hybrid configurations. Analysis of keyword frequency trends using the fieldByYear function in Bibliometrix confirms that “fuel cell vehicle” surpassed “fuel cell” as the most frequently appearing keyword after 2017, marking the transition from technology-focused to application-focused research. This temporal shift coincides with the broader movement from component-level fuel-cell research toward application-oriented vehicle and refueling- infrastructure studies [7,22].

The most recent phase (2021 to 2025) is characterized by thematic convergence around fuel cell vehicles and energy systems integration. Keyword burst analysis identifies “green hydrogen,” “machine learning,” and “digital twin” as the three most rapidly growing terms in this period, with normalized frequency growth rates of 312%, 287%, and 241% respectively relative to the 2016 to 2020 baseline. These emerging terms are not yet dominant in the keyword co-occurrence network but represent the leading edge of the field’s thematic expansion. Their appearance is discussed further in Section 6 as part of the emerging digital convergence trajectory. The prominence of fuel cell vehicles as the terminal node of the thematic evolution map supports a cautious interpretation that the field has moved from theoretical exploration toward deployment-oriented research and early commercialization.

4.10. Keyword frequency and thematic prominence

Fig. 13 presents a treemap visualization of author keyword frequency across the corpus. Each rectangle represents a keyword; size indicates frequency and color denotes thematic cluster membership as identified in the co-occurrence network.

The research landscape is structured around three dominant thematic pillars. Fuel cells (763 occurrences), fuel cell vehicles (565 occurrences), and hydrogen (516 occurrences) constitute the technological core of the field. Their prominence confirms the centrality of electrochemical conversion and vehicular integration in hydrogen transportation research.

A secondary thematic layer comprises hydrogen fuels (230 occurrences), hydrogen storage (229 occurrences), and hydrogen production (154 occurrences), capturing the supply-chain dimension of hydrogen mobility. These terms reflect persistent research efforts to improve storage density, production efficiency, and infrastructure scalability, which remain primary barriers to commercial deployment at scale.

Complementary topics including energy management (171 occurrences), energy efficiency (142 occurrences), and optimization (133 occurrences) indicate a transition from hardware development toward system-level intelligence and operational control. The recurrence of

proton exchange membrane fuel cells, secondary batteries, and charging batteries reflects technological convergence between hydrogen and electric energy systems. Environmental and policy-oriented terms including carbon dioxide (103 occurrences), greenhouse gases (101 occurrences), and fuel economy (100 occurrences) confirm continuous alignment with global decarbonization objectives. Economic and governance terms including hydrogen economy (90 occurrences) and costs (89 occurrences) highlight attention to commercialization feasibility and market readiness.

The frequency distribution confirms that hydrogen transportation research is technology-driven but increasingly incorporates environmental assessment, energy management, and economic feasibility as integral analytical dimensions. This thematic balance reflects a gradual transformation from isolated engineering design toward holistic system optimization.

4.11. Clusters by document coupling

Fig. 14 presents the thematic map derived from document coupling analysis. The horizontal axis represents centrality, measuring relevance and connectedness within the overall field. The vertical axis represents impact, reflecting the influence and maturity of each theme. The four-quadrant structure classifies research themes as motor, niche, emerging, or transversal.

The upper-right quadrant contains the motor themes, which exhibit both high centrality and high impact. Current-fed converter topologies and fuel cell vehicle systems occupy this region. These themes are both influential and structurally connected to the broader field, representing strategically important research directions with direct relevance to hydrogen vehicle commercialization. Their position in the motor quadrant is consistent with their TRL 7 to 9 maturity status, indicating that these topics have moved from research to applied engineering.

The upper-left quadrant encompasses niche themes with high impact but lower centrality. Topics including fuel cell electrochemistry, low-voltage stress management, and electric vehicle simulation are technically mature and influential within specialized domains, yet less integrated into the mainstream conceptual structure of the field. These themes represent deep technical expertise areas that support but do not anchor the broader research agenda.

The lower-left quadrant captures emerging themes with currently low centrality and moderate impact. Proton exchange membrane fuel cell optimization, energy management algorithms, and computational methods including the alternating direction method of multipliers (ADMM) appear in this region. Their low centrality reflects recent entry into the literature, while their growing publication frequency suggests



Fig. 13. Treemap of author keyword frequency in hydrogen energy and transportation research. Block size represents keyword frequency; color differentiates thematic clusters derived from co-occurrence analysis.

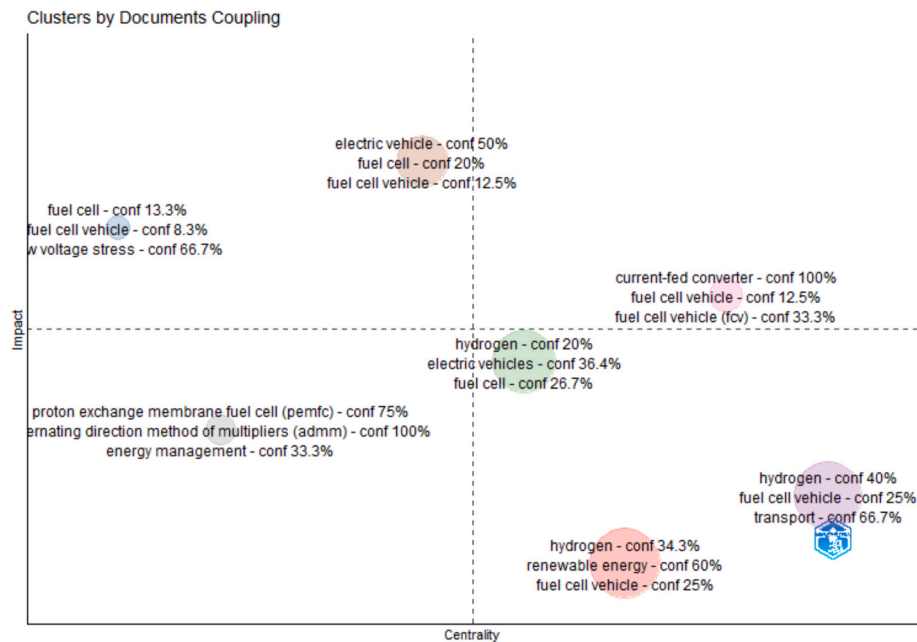


Fig. 14. Thematic map from document coupling analysis, classifying research clusters by centrality (relevance to the field) and impact (scientific influence). Quadrants correspond to motor themes, niche themes, emerging themes, and basic or transversal themes.

expanding research activity. These themes may migrate toward the motor quadrant if their publication frequency, centrality, and coupling strength continue to increase.

The lower-right quadrant represents transversal or basic themes, which are highly central to the field but exhibit moderate impact relative to the motor themes. Hydrogen, fuel cell vehicles, renewable energy, and transport occupy this zone. Their centrality reflects their foundational role in linking production, storage, infrastructure, and mobility applications across the entire field. Their moderate impact scores reflect the broad and diverse nature of the literature in these areas rather than low scientific quality.

The thematic map demonstrates a diversified and maturing research ecosystem. Motor themes confirm the applied engineering direction of the field. Emerging themes signal the entry of computational intelligence and algorithmic optimization as the next frontier. The strong presence of foundational transversal themes ensures conceptual coherence across a field that spans electrochemistry, systems engineering, environmental assessment, and transport policy.

4.12. Funding landscape

Table 12 lists the five most active funding sponsors identified in the Scopus dataset. The results show a strong concentration of public investment, led primarily by Chinese national programs.

The National Natural Science Foundation of China (NSFC) supports the largest number of publications at 215 documents, followed by the National Key Research and Development Program of China (98 documents) and the Fundamental Research Funds for the Central Universities (49 documents). Together, these three Chinese programs account for

Table 12

Top five funding sponsors supporting hydrogen energy and transportation research (2000–2025).

Rank	Funding sponsor	Documents
1	National Natural Science Foundation of China	215
2	National Key Research and Development Program of China	98
3	Fundamental Research Funds for the Central Universities	49
4	European Commission	45
5	National Research Foundation of Korea	30

362 funded documents, representing a coordinated national mechanism to accelerate hydrogen technology research across fuel cell systems, vehicle integration, and renewable hydrogen production.

Outside China, the European Commission (45 documents) and the National Research Foundation of Korea (30 documents) represent the most active non-Chinese funding sponsors in the present dataset, indicating that hydrogen mobility research is supported by both national and international public funding mechanisms.

The funding distribution indicates a strong association between public investment and scientific output in the field. The dominance of Chinese funding within the dataset is consistent with sustained national prioritization of hydrogen technologies. The European and Korean programs demonstrate policy convergence toward hydrogen as a strategic clean energy carrier. However, the concentration of funding in a small number of national programs may create structural dependency and could limit exploratory work outside officially prioritized research agendas.

4.13. Alignment with sustainable development goals

The bibliometric findings of this study can be interpreted in relation to six United Nations Sustainable Development Goals (SDGs). This mapping is best treated as an interpretive sustainability linkage rather than direct evidence of deployment impact [55]. Table 13 maps each SDG to specific thematic clusters and quantitative evidence from the bibliometric analysis.

The strongest interpretive alignment is with SDG 13 (Climate Action). The central orientation of the field is transport decarbonization, and the 18.82% CAGR, particularly the sharp post-2020 acceleration, indicates increasing scholarly attention under global net-zero policy agendas. SDG 7 (Affordable and Clean Energy) is addressed through the dominant production and storage cluster, which anchors the keyword co-occurrence network and includes 154 keyword occurrences for hydrogen production. SDG 9 (Industry, Innovation and Infrastructure) is reflected in the mapping of 400 publication sources, three leading institutional hubs, and 11,786 cross-references documenting R&D network development. SDG 11 (Sustainable Cities and Communities) is linked to 565 keyword occurrences for fuel cell vehicles and the growing applied focus on low-emission mobility. SDG 12 (Responsible

Table 13

Alignment of hydrogen energy transportation research with six United Nations Sustainable Development Goals. Evidence is drawn from the bibliometric analysis of 1,699 Scopus-indexed documents (2000–2025).

SDG	Goal	Thematic alignment	Quantitative evidence
7	Affordable and Clean Energy	Green hydrogen production; renewable electrolysis; clean energy carrier	154 hydrogen production key-word occurrences; Cluster 1 anchors the co-occurrence network; 18.82% CAGR coincides with clean energy policy momentum
9	Industry, Innovation and Infrastructure	Hydrogen refueling infrastructure; fuel cell technology; global R&D networks	400 publication sources; Tongji (163), Chongqing (114), Tsinghua (107) as leading hubs; 11,786 cross-references
11	Sustainable Cities and Communities	Urban fuel cell buses; clean freight vehicles; low-emission corridors	Fuel cell vehicles: 565 occurrences; 298 publications in 2025, the highest annual corpus output
12	Responsible Consumption and Production	Life-cycle assessment; circular economy in fuel cell materials	Greenhouse gases (101) and carbon dioxide (103) keyword occurrences; life-cycle and environmental-assessment terms present in the corpus
13	Climate Action	Transport decarbonization; net-zero emission pathways	Post-2020 publication surge and 18.82% CAGR indicate increasing scholarly attention to transport decarbonization; 32.02 average citations per document
17	Partnerships for Goals	Multilateral co-authorship; cross-continental funding consortia	23.31% international co-authorship rate; NSFC (215), European Commission (45), Korea NRF (30) as primary funders

Consumption and Production) is reflected in life-cycle and environmental-assessment terms, including greenhouse gases and carbon dioxide. SDG 17 (Partnerships for Goals) is quantitatively evidenced by the 23.31% international co-authorship rate and the multilateral funding contributions from NSFC, the European Commission, and the Korea NRF.

5. Discussion

This section interprets the bibliometric results through a systems-integration lens. The central argument advanced here is that hydrogen transportation research has matured from loosely connected component studies into an integrated knowledge system in which production, storage, refueling infrastructure, vehicle technology, lifecycle assessment, policy, and digital intelligence co-evolve within a unified analytical framework. This systems-integration perspective provides the conceptual contribution of the present study and distinguishes it from prior bibliometric work that examined the hydrogen economy, fuel cells, or storage and transportation safety as broader or more segmented domains rather than as a multimodal hydrogen mobility system [19,20,22,23].

5.1. Growth trajectory and policy alignment

As shown in Fig. 6, the temporal dynamics of the corpus reveal three clearly identifiable growth phases: an exploratory phase from 2000 to 2010, a system-development phase from 2011 to 2015, and a deployment-oriented acceleration phase from 2016 to 2025, with the strongest surge occurring after 2020. The compound annual growth rate of 18.82% reflects sustained structural expansion rather than episodic volatility. The sharp inflection after 2020 corresponds with rapid national and regional hydrogen-policy activity, including European hydrogen-infrastructure planning and China's coordinated post-2022 hydrogen-policy surge, which links hydrogen development to carbon-neutrality goals, industrial upgrading, clean energy supply, transport applications, and refueling infrastructure deployment [46,55,81].

This alignment between policy momentum and scholarly output suggests that the field's expansion is not spontaneous but institutionally coordinated. The pattern is related to, but distinct from, the broader battery-electric vehicle (BEV) transition. BEVs currently have greater market penetration and stronger near-term cost competitiveness in many light-duty and short-range applications. However, BEV deployment also depends on charging-infrastructure availability, grid stability, outage resilience, renewable-energy integration, and control strategies for EV charging stations and microgrid-connected EV loads [82,83]. Hydrogen fuel-cell pathways are therefore most defensible in use cases where payload, range, refueling time, duty cycle, or charging-infrastructure constraints weaken direct electrification. Comparative analyses of heavy goods vehicles show that BEVs can provide the lowest total cost of ownership for shorter ranges under low electricity prices,

while hydrogen fuel-cell vehicles can become competitive for longer-range or high-utilization duty cycles under favorable hydrogen price and infrastructure assumptions [15,84,85]. Therefore, the bibliometric evidence should not be interpreted as proof that hydrogen will displace battery-electric mobility. Rather, it indicates that hydrogen research is being positioned as a complementary decarbonization pathway for transport segments in which direct electrification is technically or operationally constrained: heavy-duty road transport [15,84,85], non-electrified rail corridors [8], maritime operations using hydrogen or hydrogen-derived fuels [9,50], and aviation-related applications involving liquid hydrogen, fuel-cell systems, or hydrogen-derived fuels [10,11,51]. Broad hydrogen-transport reviews support this complementary interpretation but should not be used as the sole evidence for all transport modes [4].

5.2. Disciplinary diffusion and source distribution

As illustrated in Fig. 7, the source distribution reveals progressive disciplinary diffusion. Core outlets such as *Energies*, *Applied Energy*, and *Energy Conversion and Management* concentrate the highest share of publications, reflecting the transition from single-domain electrochemistry toward system integration and environmental assessment. The growing presence of journals such as *Sustainability*, *Journal of Cleaner Production*, and *Energy Policy* confirms the incorporation of socio-technical, economic, and policy dimensions into the field.

This diversification indicates epistemic maturity. The field has moved beyond proof-of-concept engineering into a cross-sectoral discourse in which technology, economics, sustainability assessment, and governance develop together. This pattern is consistent with good practice in bibliometric interpretation, where source diffusion is read alongside thematic structure rather than treated as a stand-alone measure of research quality [61].

5.3. Geographic concentration and knowledge diffusion

The institutional and geographic distribution of research output reveals a pronounced center-periphery structure. Chinese universities, particularly Tongji University (163 papers), Chongqing University (114), and Tsinghua University (107), constitute the principal knowledge producers. They occupy the most central positions in both the co-authorship network, as mapped in Fig. 9, and the bibliographic coupling network, as shown in Fig. 10. China's degree centrality of 0.78, betweenness centrality of 0.34, and bibliographic coupling link strength of 5,847 indicate that the country is both a high-output hub and a bridge within the global knowledge structure. This dominance is consistent with the funding evidence summarized in Table 12, where the three leading Chinese funding agencies account for 362 documented publications.

The European Commission and Korea's National Research Foundation form secondary poles of influence, emphasizing regional

coordination, applied engineering, and cross-border technology development. However, the geographic asymmetry of output indicates that the global hydrogen transport discourse remains concentrated. Endogenous research capacity in many developing economies remains limited, and intellectual diffusion to Southeast Asia, Latin America, and Africa depends predominantly on transnational partnerships and technology-transfer arrangements. The co-authorship data show that peripheral countries, including Qatar, Oman, Tunisia, and Nigeria, participate mainly through bilateral links with established hubs rather than through dense intra-regional networks.

This structural dependency carries practical implications. Countries in tropical, subtropical, island, and resource-constrained regions face distinct mobility needs, grid characteristics, climate conditions, and financing constraints that require locally adapted hydrogen solutions. Strengthening south-south research consortia, regional experimental facilities, and open data-sharing platforms would improve both knowledge equity and the contextual adaptation of hydrogen technologies to diverse infrastructure conditions.

5.4. Thematic architecture and the systems integration perspective

As mapped in Fig. 11, the keyword co-occurrence network reveals a coherent thematic architecture structured around three interconnected macro-domains: hydrogen production and storage, fuel-cell vehicles and energy management, and electric-hybrid integration. The network modularity of 0.38 indicates well-separated but increasingly interconnected clusters, suggesting that the field is evolving from parallel technological tracks toward systemic convergence.

This convergence represents a shift from linear technological development to integrated systems thinking. The three clusters are no longer independent knowledge silos. The co-occurrence of lifecycle, sustainable development, and energy optimization terms across clusters demonstrates that production, conversion, infrastructure, and end-use research are increasingly being integrated under shared analytical frameworks. The “fuel cells” keyword occupies the highest degree centrality (0.64) and betweenness centrality (0.29) in the network, functioning as the conceptual anchor connecting all three domains.

The thematic evolution trajectory, presented in Fig. 12, validates this integration pattern. The field has progressed from early emphasis on alternative fuels and electrochemical feasibility from 2000 to 2010, through component consolidation from 2011 to 2015 and system optimization from 2016 to 2020, toward integrated vehicle-level solutions in the 2021 to 2025 period. This progression is consistent with the technology-readiness interpretation used in Section 4: early phases correspond mainly to TRL 2–5 activities, while the current phase reflects TRL 7–9 research supporting commercial fuel-cell vehicle and refueling-infrastructure deployment. The keyword burst analysis further confirms that “fuel cell vehicle” surpassed “fuel cell” after 2017, marking the transition from technology-focused to application-focused research.

5.5. Linking bibliometric trends to techno-economic progress

The post-2016 acceleration in publication output coincides with increasing policy support, expanding manufacturing capacity, and growing deployment activity, though hydrogen transportation remains sensitive to cost boundaries, utilization rates, electricity prices, and infrastructure availability.

In production, electrolyzer cost claims require careful boundary specification. Peer-reviewed techno-economic assessments show that electrolyzer costs and levelized hydrogen costs vary strongly by technology, stack or system boundary, electricity price, operating strategy, durability, and manufacturing scale. One bottom-up and top-down assessment reports 2020 alkaline and PEM stack-cost ranges of 242–388 EUR kW⁻¹ and 384–1071 EUR kW⁻¹, respectively, with substantial learning-driven reduction potential by 2030, while a broader applied-energy assessment emphasizes CAPEX, OPEX, efficiency,

durability, and electricity-cost sensitivity across electrolyzer technologies [86,87]. These differences explain why production and storage remain central in Cluster 1: progress is real, but reported values are not interchangeable unless system boundary, technology type, production scale, and cost year are explicitly stated.

In vehicle technology, peer-reviewed studies identify heavy-duty fuel-cell systems as promising but constrained by durability, manufacturing scale, catalyst loading, system cost, and duty-cycle requirements that exceed light-duty benchmarks [85]. Recent hydrogen-mobility reviews likewise show that hydrogen fuel-cell vehicle deployment depends on parallel progress in green hydrogen production, fuel-cell durability, refueling infrastructure, regulatory support, and investment coordination [88,89], consistent with the post-2016 dominance of Cluster 2.

In infrastructure, peer-reviewed station-level reviews show that hydrogen refueling infrastructure has expanded but continues to face major technical, economic, siting, utilization, and corridor-planning barriers [14,89]. This confirms the infrastructure-deployment paradox: real-world station expansion remains far below what mass-market hydrogen mobility would require.

Collectively, these techno-economic developments provide empirical grounding for the bibliometric growth curves and thematic shifts observed in this study. The coupling between manufacturing scale-up, public investment, station deployment, and rising publication output suggests a mutually reinforcing feedback loop between research investment and technology progress, strongest where policy, funding, and industrial programs are coordinated, especially in China, Germany, Japan, South Korea, and selected European Union initiatives.

5.6. Collaboration networks and structural asymmetries

The co-authorship network reveals a maturing but unevenly distributed research ecosystem. Central economies, led by China, Germany, the United Kingdom, Japan, and the United States, function as network hubs that coordinate transnational collaborations and generate methodological standardization. The modularity of 0.41 confirms the presence of distinct regional clusters, most notably a tightly coupled European cluster consistent with Horizon-funded coordination and an East Asian cluster anchored by China and Japan.

Emerging economies such as India, Malaysia, and Thailand contribute regionally but often depend on cross-border partnerships for resource-intensive experimental research. This spatial configuration has both benefits and risks. It enhances data sharing and technical diffusion, but it can also reinforce dependency structures in which developing countries contribute local case studies while established hubs provide methodological frameworks, experimental facilities, and high-impact publication venues. Expanding autonomous experimental capabilities in developing regions would improve research resilience and the contextual relevance of hydrogen solutions for diverse mobility environments.

5.7. Funding structure and innovation risk

As summarized in Table 12, the funding landscape confirms structural coupling between public investment and scientific productivity. The three Chinese national funding programs together support 362 documented publications, representing the single largest concentration of research investment in the field. European and Korean programs complement this through collaborative frameworks emphasizing cross-border infrastructure harmonization, applied materials development, and deployment-oriented engineering.

However, dependence on public-sector financing introduces concentration risk. Publicly funded programs tend to prioritize incremental engineering improvements within established technology roadmaps, which may constrain exploratory or disruptive innovation. Diversifying funding sources through industrial partnerships, venture-backed pilot

projects, and cross-sector consortia could foster methodological pluralism and accelerate the translation of research into market-ready technologies. More complete and standardized reporting of funding acknowledgment data would also enable future bibliometric studies to assess how financial inputs translate into intellectual, technical, and commercial outputs.

5.8. Contradictions and unresolved tensions in the literature

Despite the overall trajectory toward maturity, several contradictions and unresolved tensions in the hydrogen transportation literature require explicit recognition.

First, there is an infrastructure-deployment paradox. Sustained publication activity on hydrogen refueling stations contrasts with slow real-world deployment outside leading early markets. Global station counts have increased, but coverage remains geographically concentrated and far below what mass-market hydrogen mobility would require [14,89]. The literature frequently projects optimistic infrastructure buildout scenarios that are not matched by realized investment, permitting speed, or hydrogen supply availability. This gap reflects a structural mismatch between academic modeling assumptions and policy execution rather than evidence of commercial readiness.

Second, regional research priorities diverge in ways obscured by global aggregation. Chinese output is strongly oriented toward fuel-cell vehicle powertrain optimization and energy-management algorithms. European research emphasizes green hydrogen production, life-cycle assessment, and cross-border infrastructure coordination. Japanese and Korean research focuses on materials durability, cost reduction, and commercial-scale deployment. These emphases are complementary in aggregate but fragmented in practice, limiting direct transferability across national contexts.

Third, the growing discourse on hydrogen for aviation and maritime applications remains less mature than the road-transport literature. Maritime and aviation keywords are comparatively underrepresented relative to road-vehicle and fuel-cell-vehicle terms, despite their prominence in policy roadmaps. Studies confirm strategic potential but also emphasize unresolved constraints in on-board storage, safety, infrastructure, fuel logistics, and cost [8,10,11,50]. Multimodal hydrogen applications should therefore be discussed as strategically important but comparatively under-developed research fronts.

5.9. Actionable insights for stakeholders

The bibliometric evidence compiled in this study supports several specific recommendations for researchers, industry stakeholders, and policymakers.

For researchers: Three high-priority research gaps emerge from the keyword co-occurrence and thematic evolution analyses. First, hydrogen-electric hybridization control strategies that integrate sensor data, physics-informed modeling, and validated machine-learning approaches remain early-stage but fast growing. Second, life-cycle assessment of hydrogen mobility should move beyond production emissions to include compression, distribution, refueling, water use, maintenance, and end-of-life management of fuel-cell and storage-system materials [18,90,91]. Third, maritime, aviation, and rail applications require dedicated multimodal research programs because the current corpus is still dominated by road-vehicle applications [8,10,50].

For industry stakeholders: The thematic map identifies energy management, PEMFC optimization, algorithmic control, and digital-twin-enabled diagnostics as emerging research fronts that may migrate toward motor-theme status in the next five-year period. Firms developing hydrogen vehicle platforms should prioritize validation under real duty cycles, interoperability with refueling infrastructure, durability monitoring, and safety-certified digital control architectures [92–94]. Partnerships with leading Chinese, European, Japanese, and Korean institutions can provide access to established experimental

infrastructure, but industry consortia should also invest in open test protocols so that results are transferable across regions and vehicle classes.

For policymakers: The geographic concentration of output and funding highlights a knowledge-equity challenge. Policymakers in developing regions should prioritize regional hydrogen research centers, shared pilot corridors, and bilateral or multilateral research agreements with hub countries. At the national level, the strong association between public funding and publication output indicates that sustained, long-horizon investment is a primary determinant of research capacity. Policy packages should connect research funding with standards development, demand aggregation, station-utilization planning, and transparent carbon-intensity certification so that scientific growth is translated into deployable transport systems [13,14,95,96].

5.10. Maturity assessment and future trajectory

A comparative view of hydrogen mobility research maturity is presented in Fig. 15. The radar chart should be interpreted as a qualitative synthesis of the bibliometric patterns, TRL interpretations, deployment indicators, and techno-economic evidence discussed in Sections 4 and 5. It is not intended as an independent quantitative maturity model or as a direct measurement of technology readiness.

The radar visualization indicates that vehicle technology and policy readiness occupy comparatively higher maturity positions within the hydrogen transportation ecosystem. This interpretation is consistent with commercial fuel-cell vehicle deployment, heavy-duty demonstration activity, and national or regional hydrogen strategies in multiple jurisdictions [55,81,85,88]. By contrast, production and storage remain major system-level bottlenecks because cost, scale, compression, liquefaction, storage density, and distribution constraints remain unresolved across many deployment contexts [38,87,89]. Infrastructure occupies an intermediate position, reflecting continued refueling-station expansion but also strong geographic unevenness and corridor-planning limitations [14,89]. Digital intelligence is the least mature dimension: machine learning and digital twin terms are growing rapidly, but they remain peripheral in the co-occurrence network and should therefore be treated as early-stage bibliometric signals rather than mature deployment evidence [79,94].

The visual scores in Fig. 15 should therefore be read as ordinal and interpretive indicators of relative maturity and opportunity, not as absolute numerical values. Their purpose is to summarize the uneven development of the hydrogen transportation ecosystem across production, storage, infrastructure, vehicle technology, digital intelligence, and policy readiness.

Overall, the bibliometric evidence demonstrates that hydrogen energy for transportation has transitioned from an emergent topic to a strategically coordinated research domain. The most critical challenge ahead lies not only in technological feasibility but also in socio-economic scalability, infrastructure coordination, standards harmonization, and equitable global knowledge diffusion. Addressing these challenges through coordinated investment, transparent certification, standardized protocols, and inclusive international partnerships will determine whether hydrogen becomes a practical component of carbon-neutral mobility systems.

6. Future research directions

As hydrogen energy for transportation reaches greater technological and institutional maturity, the next stage of research will increasingly intersect with digitalization, artificial intelligence, and data-driven systems engineering. This section outlines future research trajectories grounded in the bibliometric evidence presented in Section 4. The keyword burst analysis identified “green hydrogen,” “machine learning,” and “digital twin” as the three fastest-growing terms in the 2021 to 2025 period, with normalized frequency growth rates of 312%,



Fig. 15. Qualitative synthesis radar for hydrogen mobility research maturity and future opportunity across six dimensions: production, storage, infrastructure, vehicle technology, digital intelligence, and policy readiness. The radar scores are interpretive ordinal indicators synthesized from bibliometric results, TRL discussion, and techno-economic context.

287%, and 241%, respectively, relative to the 2016 to 2020 baseline. Additional emerging terms, including “blockchain,” “IoT,” and “quantum computing,” showed growth rates between 120% and 180% over the same period, but their absolute frequencies remain low. These frontiers are therefore framed as early-stage or prospective directions rather than as mature bibliometric clusters.

As summarized in Table 14, these research frontiers differ in bibliometric maturity, technological readiness, and evidentiary strength. Fig. 16 presents a layered digital-physical architecture that illustrates how governance, sensing, data integration, cognitive computing, and physical hydrogen mobility assets can be coordinated to operationalize these future research directions.

6.1. Artificial intelligence for optimization and maintenance

Artificial intelligence, including machine learning, deep learning, and reinforcement learning, is positioned to support hydrogen transportation across control, diagnostics, and maintenance applications. The keyword “machine learning” showed 287% frequency growth in the 2021 to 2025 period, confirming rapid emergence as a research focus. AI algorithms can support fuel-cell power-management optimization, degradation prediction, and adaptive operating strategies that balance hydrogen consumption, load demand, and durability constraints [79,97].

However, this frontier should be interpreted cautiously. Existing studies are still more concentrated in simulation, energy-management design, and diagnostic modeling than in large-scale operational

validation across hydrogen fleets. Priority areas include explainable AI architectures, physics-informed learning, data-fusion methods for heterogeneous sensor inputs, benchmark datasets, and real-world validation protocols for AI-driven fleet management and predictive maintenance.

6.2. Large language models for hydrogen engineering systems

Large language models represent the least bibliometrically established frontier among the digital technologies examined here. The term “large language model” does not yet appear as a stable standalone keyword in the co-occurrence network, and its absolute frequency in the corpus remains below 10 occurrences, concentrated in 2024 and 2025. The following discussion is therefore a prospective research outlook grounded in the broader AI trajectory rather than a mature finding from the corpus. Recent transportation LLM bibliometric work confirms that language-model applications are expanding in transport research more broadly, but this evidence should not be interpreted as hydrogen-specific validation [98].

Future research could examine whether domain-adapted language models can assist hydrogen engineering workflows by organizing technical reports, simulation notes, maintenance records, safety procedures, and sensor-log summaries. Potential applications include structured design support, documentation generation, maintenance-log triage, and retrieval-augmented access to standards or test protocols. These uses should remain human-reviewed and evidence-traceable because hydrogen systems involve safety-critical components, high-pressure

Table 14

Research frontiers and strategic directions for hydrogen transportation systems. Keyword signals combine normalized growth rates where meaningful with absolute-frequency qualifiers for low-count emerging terms. Growth rates are based on the normalized frequency analysis of the 2021 to 2025 period relative to the 2016 to 2020 baseline.

Research Frontier	Keyword signal*	Key research objectives	Emerging tools and methodologies
Artificial intelligence	287%	Real-time energy management, predictive maintenance, adaptive control of hybrid vehicles, and fleet coordination under uncertainty.	Reinforcement learning, multi-agent optimization, physics-informed neural networks, explainable AI, digital feedback systems.
Large language models	<10†	Prospective cognitive support for component design, simulation guidance, diagnostics, maintenance log analysis, and documentation generation.	Domain-adapted transformer models, retrieval-augmented engineering workflows, human-reviewed maintenance agents, digital-twin-linked inference, validated pipelines.
Quantum computing	~150%	Prospective catalyst and membrane discovery, logistics optimization, and atomistic reaction-mechanism modeling.	Variational quantum eigensolvers, quantum approximate optimization algorithms, hybrid quantum-classical pipelines, quantum molecular simulation.
IoT and cyber-physical systems	~160%	Real-time monitoring, leak detection, and adaptive operation across hydrogen production, storage, distribution, and refueling assets.	Edge computing, federated analytics, low-power telemetry, distributed safety systems.
Digital twins	241%	Virtual replicas of production assets, refueling stations, vehicles, and supply networks; real-time feedback for optimization, fault detection, and safety assessment.	Hybrid AI-physics models, cyber-physical co-simulation, adaptive parameter identification, scenario-planning engines.
Blockchain and trust systems	~135%	Certification and traceability of hydrogen origin and carbon intensity; prospective trading and compliance verification.	Permissioned ledgers, smart contracts, verifiable credentials, carbon-intensity audit trails.
Multimodal integration	N/A	Extension of hydrogen to rail, maritime, aviation, and multi-energy hubs linking hydrogen, electricity, ports, airports, and freight corridors.	System-of-systems simulation, multi-energy hub optimization, cross-modal protocols, techno-economic and environmental models.
Circular economy	N/A	Lifecycle closure through recovery and recycling; resource-efficient design pathways; net-zero potential evaluation.	Life-cycle assessment, material-flow analysis, circular design models, waste-to-hydrogen strategies, ISO-aligned indicators.

*For artificial intelligence, digital twins, quantum computing, IoT, and blockchain, values report normalized keyword frequency growth for the 2021 to 2025 period relative to the 2016 to 2020 baseline, computed from fieldByYear analysis in Bibliometrix. For large language models, the value reports absolute corpus frequency because the growth rate is not meaningful at such a low count. N/A indicates that the frontier is defined by thematic gaps rather than by a single emerging keyword. † Absolute corpus frequency ($n < 10$).

operation, and strict certification requirements.

A second prospective direction is the coupling of language models with computational fluid dynamics, electrochemical simulation, and digital-twin environments. Such systems could help generate simulation checklists, parameter-sweep plans, sensitivity-analysis routines, or diagnostic hypotheses. They should not be treated as autonomous engineering decision makers. Verification and validation protocols combining uncertainty quantification, source traceability, expert review, and reproducibility checks are necessary before language-model outputs can be used in safety-relevant hydrogen engineering workflows.

6.3. Quantum computing for materials and network optimization

Quantum computing may eventually contribute to selected hydrogen-system problems, particularly energy-domain optimization, exploratory materials screening for green hydrogen and ammonia production, and combinatorial optimization in logistics or infrastructure planning. Energy-domain reviews identify quantum computing as a potential long-term tool for materials and optimization problems, but the present corpus does not yet provide evidence that quantum methods outperform classical approaches in hydrogen transportation applications [99].

The keyword “quantum computing” showed a growth rate of approximately 150% in the 2021 to 2025 period, but its absolute frequency remains below 15 occurrences. It should therefore be framed as a pre-emergent research direction. Near-term work should focus on clearly benchmarked hybrid quantum-classical demonstrations, transparent comparisons against classical optimization baselines, and problem formulations grounded in actual hydrogen logistics and refueling-station planning needs. Conventional hydrogen refueling-station location and supply-chain optimization remains the current operational baseline for this class of problems [100]; quantum computing is therefore retained here as a prospective frontier, not as evidence of current deployment readiness.

6.4. Internet of things and sensor networks

IoT-enabled sensing and communication form the data layer of emerging smart hydrogen systems. The keyword “IoT” showed a growth rate of approximately 160% in the 2021 to 2025 period, although its absolute frequency remains modest, placing it at an early-stage bibliometric presence. Distributed sensor networks in hydrogen generators, renewable hydrogen plants, storage systems, and refueling infrastructure can provide real-time data on pressure, temperature, humidity, vibration, and leak-detection indicators [101,102]. For transport applications, these sensing architectures are most relevant when linked to safety monitoring, station reliability, and secure data exchange across connected infrastructure.

Integration of IoT data with edge computing and cloud analytics can support adaptive control, predictive diagnostics, and safety assurance. However, increased connectivity also expands the cybersecurity and data-governance burden. Future research should therefore integrate sensor design with secure communication architectures, failure-mode analysis, privacy-preserving analytics, and certification procedures for safety-critical hydrogen infrastructure [103].

6.5. Digital twins and virtual simulation platforms

Digital twins are virtual representations of physical hydrogen assets that enable continuous simulation, monitoring, and optimization. The keyword “digital twin” showed the third-highest growth rate in the corpus (241%) during 2021 to 2025, indicating rapid emergence as a research priority. Existing evidence is strongest for green hydrogen production and electrolyzer-fleet applications, where digital twins and machine learning can support advanced monitoring, control, and scale-up of hydrogen production assets [104,105]. Recent hydrogen-specific

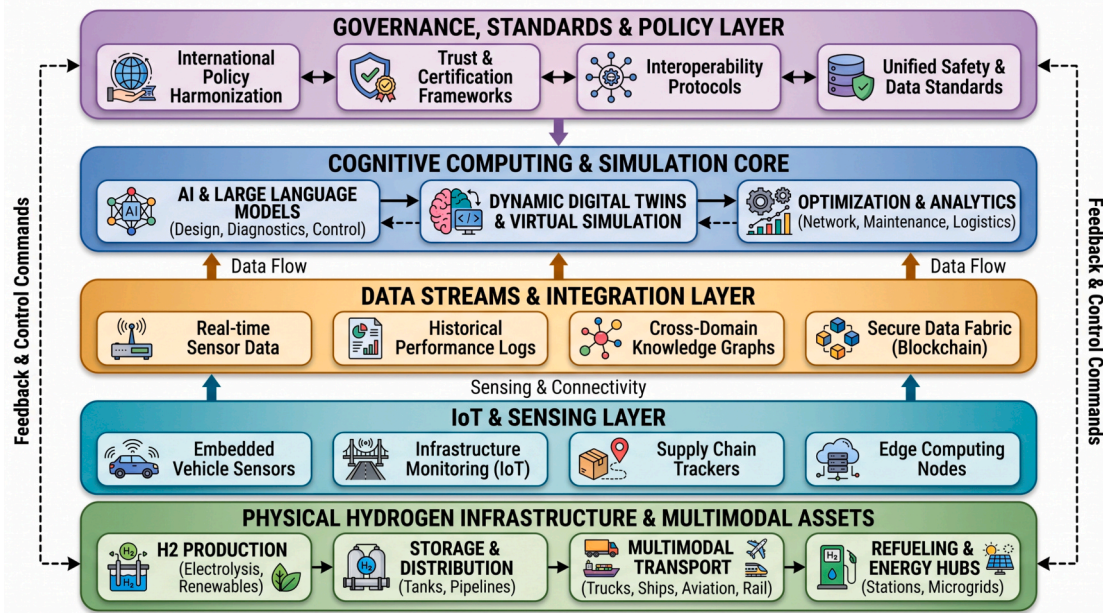


Fig. 16. Layered digital-physical architecture for intelligent hydrogen transportation systems. The framework connects governance and standards, cognitive computing, data integration, IoT-enabled sensing, and physical hydrogen infrastructure through bidirectional feedback and control loops.

digital-twin research also frames digital twins as tools for improving safety, reliability, predictive maintenance, and optimized operation across hydrogen systems [94].

For hydrogen transportation, the next step is to extend digital-twin architectures from individual production or component models toward integrated vehicle–station–grid and corridor-level platforms. Multi-scale twins could support safety scenario testing, station-utilization analysis, degradation monitoring, and emergency-response planning. Research priorities include standardizing twin architectures, validating model fidelity against operational data, integrating AI-based feedback loops, and extending twin frameworks to regional hydrogen corridors and multimodal logistics networks.

6.6. Blockchain and decentralized trust systems

The keyword “blockchain” showed a growth rate of approximately 135% from 2021 to 2025, but its absolute frequency remains below 20 occurrences. Blockchain should therefore be framed as a pre-emergent rather than established research front in hydrogen transportation. Its strongest near-term relevance lies in traceability, certification, and carbon-intensity accounting for green hydrogen supply chains [95,106].

Immutable ledgers and verifiable credentials can record hydrogen production pathways, transfers, certificates, and component histories. Smart contracts may support future compliance verification or energy-market transactions, but these applications require interoperability with regulatory schemes, measurement protocols, and cybersecurity controls. As hydrogen networks become more digitally connected, cybersecurity research for natural-gas and hydrogen infrastructure becomes directly relevant to the design of secure data exchange and audit trails [103].

6.7. Multimodal transportation and system integration

Future research must extend hydrogen analysis beyond road transport to include rail, maritime, aviation, ports, airports, and freight corridors within broader clean mobility systems. Hydrogen’s high gravimetric energy density makes it potentially relevant for long-range and high-utilization applications where battery-only solutions face payload, range, or charging-time constraints. This multimodal relevance

must be supported with mode-specific evidence: hydrogen fuel-cell trains are being evaluated for non-electrified rail routes [8]; hydrogen and hydrogen-derived fuels such as ammonia and methanol are being investigated for maritime decarbonization [9,50]; and liquid-hydrogen aircraft systems and hydrogen aviation pathways remain active but technically constrained research fronts [10,11,51]. Broad hydrogen-transport reviews support the cross-modal relevance of hydrogen but also emphasize unresolved challenges related to storage volume, safety, infrastructure, and cost [4].

Hydrogen airport ecosystems combining on-site electrolysis, liquid or compressed storage, ground-service vehicles, and aviation fuel pathways illustrate the convergence of power, mobility, and infrastructure. At seaports, hydrogen or hydrogen-derived fuels can support vessels, drayage trucks, cargo-handling equipment, and nearby industrial users. Renewable integration in hydrogen refueling stations is a particularly important interface between transport infrastructure and energy-system planning [44]. Modeling such systems through coupled simulations of grid, mobility, and hydrogen flows represents a critical frontier for cross-sectoral decarbonization. As noted in Section 5, maritime and aviation keywords remain comparatively underrepresented in the corpus, confirming that these applications remain underexplored relative to their strategic importance.

6.8. Circular economy and sustainability metrics

Long-term viability of hydrogen transportation requires lifecycle closure through resource-efficient design, recovery, recycling, and end-of-life management. Fuel-cell membranes, platinum-group catalysts, bipolar plates, and carbon-fiber storage tanks all create material-management challenges that are not captured by tailpipe-emission metrics. Life-cycle assessment should therefore extend beyond hydrogen production to include water footprint, electricity source, compression, liquefaction, distribution, refueling, material extraction, maintenance, and disposal pathways [3,18,26,27,49,90]. End-of-life fuel-cell management is particularly important because spent membrane electrode assemblies contain platinum-group metals whose recovery affects both environmental performance and resource security [91].

The keyword data show that life-cycle and circular-economy terms

are present in the corpus but infrequently co- occurring, indicating fragmented coverage. Dedicated research programs that integrate material-flow analysis, techno- economic modeling, and circular design are needed to evaluate whether hydrogen transportation systems can deliver net climate benefits while reducing critical-material pressure and end-of-life waste.

6.9. Major open challenges

Despite the progress documented in the bibliometric analysis, hydrogen transportation continues to face systemic challenges. Table 15 summarizes six challenge areas and the corresponding research and policy needs.

Scalability remains the foremost constraint. Global low-emission hydrogen production and infrastructure deployment are still far below the levels implied by announced net-zero strategies, and many projects remain at early development stages rather than final investment decision [46,54,89]. Achieving scalability requires progress in modular plant design, low-cost electrolyzer manufacturing, storage and distribution planning, and investment frameworks that connect production with regional transport corridors.

Durability and lifetime optimization of fuel cells and storage systems pose persistent engineering challenges. Catalyst degradation, membrane thinning, impurity sensitivity, and thermal stress continue to limit stack lifetime and raise system cost. Combining advanced materials research with digital diagnostics and predictive degradation models is essential

Table 15

Major open challenges in hydrogen transportation systems and strategic research needs.

Challenge area	Core limitations	Strategic research and policy needs
Scalability of production and infrastructure	Insufficient renewable hydrogen production; limited electrolyzer capacity; slow deployment of compression, liquefaction, storage, and refueling systems; mismatch between supply locations and transport demand.	Modular low-cost plant design; integrated regional planning; improved supply-chain modeling; investment frameworks connecting production with transport corridors.
Durability and lifetime optimization	Catalyst degradation, membrane wear, impurity sensitivity, and thermal stress reduce reliability and increase cost; limited real-time diagnostic capability.	Advanced materials development; sensor-based continuous monitoring; predictive degradation models; accelerated stress-testing frameworks.
Interoperability and standardization	Inconsistent protocols for pressure levels, nozzle design, safety codes, permitting, and certification across national boundaries.	Unified engineering standards; global certification programs; cross-national safety testing; harmonized refueling protocols.
Data governance and cybersecurity	Vulnerable data exchange channels; lack of secure interfaces among vehicles, stations, production sites, storage assets, and control platforms.	Secure communication architectures; privacy-preserving analytics; audit trails; digital-twin verification; coordinated cybersecurity policies.
Regulatory fragmentation	Different definitions of green hydrogen; inconsistent subsidies; misaligned carbon accounting; fragmented safety regulations.	International policy harmonization; transparent certification schemes; unified carbon-intensity metrics; evidence-based subsidy design.
Sustainability and life-cycle assessment	Uncertain environmental impacts across the full life-cycle; water-use concerns; end-of-life management challenges for fuel-cell and storage materials.	Comprehensive life-cycle analysis; water-footprint modeling; circular design strategies; end-of-use recycling frameworks.

for meeting commercial reliability requirements [92,93].

Interoperability and standardization represent practical deployment barriers, particularly for cross-border transport and corridor-based freight systems. Mismatches in pressure levels, nozzle designs, safety codes, permitting rules, and certification procedures hinder international deployment and fleet interoperability [13,14]. A globally aligned set of engineering standards and certification pathways is needed to support seamless vehicle and station operation.

Data governance and cybersecurity become more important as hydrogen systems are linked through sensors, cloud platforms, digital twins, and automated control systems. Vulnerabilities in data exchange or access control may compromise safety and operational continuity. Research on privacy-preserving data sharing, secure control architectures, transparent audit trails, and cybersecurity standards is therefore necessary for the digital transformation of hydrogen infrastructure [103].

Regulatory fragmentation continues to impede market development. Countries differ in hydrogen color definitions, subsidy mechanisms, certification rules, and carbon-accounting frameworks. Harmonization of regulatory frameworks and sector-specific adoption policies is necessary to build investor confidence and accelerate deployment at scale [55,81,96].

Sustainability assessment must remain central to ensure that hydrogen-based transport genuinely reduces emissions and resource consumption. Future sustainability metrics should incorporate water use, material extraction, energy conversion losses, infrastructure utilization, and end-of-life management for fuel-cell and storage systems [18,26,27,90,91]. Collectively, these challenges underscore the need for a unified research-policy-industry collaboration model and open, interoperable digital infrastructures that support transparent coordination across production, distribution, refueling, and transport operations.

7. Conclusion

This study provides a comprehensive scientometric assessment of the evolution, intellectual structure, and strategic direction of hydrogen energy research for transportation systems. Through systematic analysis of 1,699 Scopus-indexed journal articles published between 2000 and 2025, the study identifies principal growth trajectories, collaboration networks, thematic clusters, and emerging frontiers. The integrated analytical workflow combining Bibliometrix, VOSviewer, and Python, validated through cross-tool consistency testing (Jaccard $J \geq 0.84$ across all keyword clusters), supports the reproducibility and reliability of the findings.

Five principal findings emerge from the analysis. First, the field has undergone sustained structural expansion, with a compound annual growth rate of 18.82% across the study window. The post-2020 acceleration reflects major national hydrogen strategies and global net-zero commitments. Second, China, Germany, and the United Kingdom are the central research contributors, supported by coordinated public funding from the NSFC (215 papers), the European Commission (45 papers), and the Korea NRF (30 papers). The co-authorship network (density = 0.30, modularity.

= 0.41) reveals a globally connected but geographically asymmetric collaboration structure. Third, three dominant thematic clusters define the intellectual architecture of the field: hydrogen production and storage infrastructure (Cluster 1, TRL 4 to 8), fuel cell vehicle technologies and energy management (Cluster 2, TRL 6 to 9), and electric-hybrid system integration (Cluster 3, TRL 4 to 9). Fourth, keyword burst analysis identifies an emerging digital convergence frontier: green hydrogen (312% growth), machine learning (287%), and digital twin (241%) are the fastest-growing terms in the 2021 to 2025 period. Fifth, the field has matured from isolated component research toward an integrated systems perspective, representing the central conceptual contribution of this study.

This study recognizes several methodological limitations. The

analysis relies on Scopus as the sole primary database, with an estimated 88% overlap with Web of Science; records unique to WoS did not materially alter the principal findings. Keyword co-occurrence analysis depends on author-assigned keywords, which are absent for 10.59% of records. The English-language restriction may undercount contributions published in national-language outlets, particularly Chinese journals. Manual screening, although validated at Cohen's $\kappa = 0.87$, carries residual subjectivity in borderline cases. The emerging digital technology discussion reflects informed projection based on keyword trend data rather than mature bibliometric clusters. Funding analysis relies solely on acknowledgment metadata, which underrepresents industrial sponsors.

Despite these limitations, this study provides a rigorous and reproducible evidence base for understanding the scientific landscape of hydrogen energy in transportation. The findings support evidence-based decision-making for researchers, engineers, and policymakers. Future work should integrate bibliometrics with techno-economic assessment, life-cycle evaluation, patent analysis, and advanced computational intelligence to capture the full scope of the hydrogen mobility transition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) utilized GPT-5.1 in order to assist with grammar correction, language refinement, and overall clarity of expression. After using this tool, the author(s) thoroughly reviewed and edited the content as needed to ensure accuracy, integrity, and alignment with the intended scholarly rigor. The author(s) take full responsibility for the final content of the publication. AI and AI-assisted technologies were not used to generate, analyse, or interpret research data, nor to produce or alter scientific conclusions.

CRediT authorship contribution statement

Mahbub Hassan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Pretom Sarkar:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Mohammad Bin Amin:** Funding acquisition. **Muhammad Fitra Zambak:** Writing – review & editing, Resources.

Informed consent

Not applicable. This study does not involve human participants of any kind.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data presented in this study are available on request from the

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References

- [1] Creutzig F, Jochem P, Edelenbosch OY, Mattauch L, van Vuuren DP, McCollum D, et al. Transport: a roadblock to climate change mitigation? *Science* 2015;350(6263):911–2. <https://doi.org/10.1126/science.aac8033>.
- [2] Maria Sharmina, Oreane Y Edelenbosch, Charlie Wilson, Rebecca Freeman, David EHJ Gernaat, Paul Gilbert, Alice Larkin, Emily W. Littleton, Michael Traut, Detlef P van Vuuren, Naomi E. Vaughan, Richard Wood, Corinne Le Quéré. Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C. *Climate Policy*. 21(4):455–74, 2021. 10.1080/14693062.2020.1831430.
- [3] Anand C, Chandrara B, Nithiya P, Akshaya M, Tamizhdurai P, Shoba G, Subramani A, Kumaran R, Yadav KK, Gacem A, Bhutto JK, Alreshidi MA, Alam MW. Green hydrogen for a sustainable future: A review of production methods, innovations, and applications. *Int J Hydrogen Energy* 2025;111:319–41. <https://doi.org/10.1016/j.ijhydene.2025.02.257>.
- [4] Alreshidi MA, Yadav KK, Shoba G, Amel Gacem S, Padmanabhan S, Ganesan LG, et al. Hydrogen in transport: a review of opportunities, challenges, and sustainability concerns. *RSC Adv* 2025;15:23874–909. <https://doi.org/10.1039/d5ra02918j>.
- [5] Yue M, Lambert H, Pahon E, Roche R, Jemei S, Hissel D. Hydrogen energy systems: a critical review of technologies, applications, trends and challenges. *Renew Sustain Energy Rev* 2021;146:111180. <https://doi.org/10.1016/j.rser.2021.111180>.
- [6] Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, Shah N, Ward KR. The role of hydrogen and fuel cells in the global energy system. *Energy Environ Sci* 2019;12(2):463–91. <https://doi.org/10.1039/C8EE01157E>.
- [7] Fakhreddine O, Gharbia Y, Derakhshandeh JF, Amer AM. Challenges and solutions of hydrogen fuel cells in transportation systems: a review and prospects. *WORLD Electr Veh J* 2023;14(6):156. <https://doi.org/10.3390/wevj14060156>. ISSN 2032-6653.
- [8] Ding D, Xiao-Yu W. Hydrogen fuel cell electric trains: technologies, current status, and future. *Appl Energy Combust Sci* 2024;17:100255. <https://doi.org/10.1016/j.jaecs.2024.100255>.
- [9] Shi J, Zhu Y, Feng Y, Yang J, Xia C. A prompt decarbonization pathway for shipping: green hydrogen, ammonia, and methanol production and utilization in marine engines. *Atmosphere* 2023;14(3):584. <https://doi.org/10.3390/atmos14030584>.
- [10] Ebrahimi A, Rolt A, Jafari S, Anton JH. A review on liquid hydrogen fuel systems in aircraft applications for gas turbine engines. *Int J Hydrogen Energy* 2024;91:88–105. <https://doi.org/10.1016/j.ijhydene.2024.10.121>. ISSN 0360-3199.
- [11] Alreshidi MA, Yadav KK, Amel Gacem S, Padmanabhan S, Ganesan S, Mahalingam TV, Kumar PS, Thajudeen KY, Fallatah AM, Ahmed MM, Shoba G, Kavitha C, Tamizhdurai P, Khalid M. Zero-emission transportation and aviation through green hydrogen innovation. *Mater Today Sustain* 2025;32:101264. <https://doi.org/10.1016/j.mtsust.2025.101264>.
- [12] Eberle U, Müller B, von Helmolt R. Fuel cell electric vehicles and hydrogen infrastructure: status 2012. *Energy Environ Sci* 2012;5(10):8780–98. <https://doi.org/10.1039/C2EE22596D>.
- [13] Genovese M, Cigolotti V, Jannelli E, Fragiaco P. Current standards and configurations for the permitting and operation of hydrogen refueling stations. *Int J Hydrogen Energy* 2023;48(51):19357–71. <https://doi.org/10.1016/j.ijhydene.2023.01.324>.
- [14] Genovese M, Fragiaco P. Hydrogen refueling station: overview of the technological status and research enhancement. *J Storage Mater* 2023;61:106758. <https://doi.org/10.1016/j.jest.2023.106758>.
- [15] Cameron Rout H, Li VD, Wadud Z. A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel. *Heliyon* 2022;8(12):e12417. <https://doi.org/10.1016/j.heliyon.2022.e12417>.
- [16] Magnino A, Marocco P, Saarikoski A, Ihonon J, Rautanen M, Gandiglio M. Total cost of ownership analysis for hydrogen and battery powertrains: a comparative study in finnish heavy-duty transport. *J Storage Mater* 2024;99:113215. <https://doi.org/10.1016/j.jest.2024.113215>.
- [17] Ajanovic A, Haas R. Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy* 2018;123:280–8. <https://doi.org/10.1016/j.enpol.2018.08.063>.
- [18] Rinawati DI, Keeley AR, Takeda S, Managi S. A systematic review of life cycle assessment of hydrogen for road transport use. *Prog Energy* 2022;4(1):012001. <https://doi.org/10.1088/2516-1083/ac34e9>.
- [19] Yap J, McLellan B. A historical analysis of hydrogen economy research, development, and expectations, 1972 to 2020. *Environments* 2023;10(1):11. <https://doi.org/10.3390/environments10010011>.
- [20] Kar SK, Harichandan S, Roy B. Bibliometric analysis of the research on hydrogen economy: an analysis of current findings and roadmap ahead. *Int J Hydrogen Energy* 2022;47(20):10803–24. <https://doi.org/10.1016/j.ijhydene.2022.01.137>.
- [21] Osman SH, Yatim NSM, Elham OSJ, Shaari N, Zakaria Z. Three decades of hydrogen energy research: a bibliometric analysis on the evolution of green hydrogen technologies. *Sustain Energy Fuels* 2025;9:3182–202. <https://doi.org/10.1039/d5se00254k>.
- [22] Agyekum EB, Odoi-Yorke F, Abbey AA, Ayetor GK. A review of the trends, evolution, and future research prospects of hydrogen fuel cells: a focus on

- vehicles. *Int J Hydrogen Energy* 2024;72:918–39. <https://doi.org/10.1016/j.ijhydene.2024.05.480>.
- [23] Tang J, Chen C, Wang B, Li C, Li J, Yang M, Salzano E. A bibliometric review of hydrogen storage and transportation safety research. *J Pipeline Sci Eng* 2025: 100425. <https://doi.org/10.1016/j.jpse.2025>.
- [24] Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *Int J Hydrogen Energy* 2014;39(1):1–12. <https://doi.org/10.1016/j.ijhydene.2013.10.060>.
- [25] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production methods: a review. *Renew Sustain Energy Rev* 2014;40:106–22. <https://doi.org/10.1016/j.rser.2014.07.180>.
- [26] Blohm M, Dettner F. Green hydrogen production: integrating environmental and social criteria to ensure sustainability. *Smart Energy* 2023;11:100112. <https://doi.org/10.1016/j.segy.2023.100112>.
- [27] Cremonese L, Mbungu GK, Quitoow R. The sustainability of green hydrogen: an uncertain proposition. *Int J Hydrogen Energy* 2023;48(51):19422–36. <https://doi.org/10.1016/j.ijhydene.2023.01.350>.
- [28] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. *Nat Energy* 2019;4(3):216–22. <https://doi.org/10.1038/s41560-019-0326-1>.
- [29] Oni AO, Anaya K, Giwa T, Lullo GD, Kumar A. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Convers Manage* 2022;254:115245. <https://doi.org/10.1016/j.enconman.2022.115245>.
- [30] Pruvost F, Cloete S, del Pozo CA, Zaabou A. Blue, green, and turquoise pathways for minimizing hydrogen production costs from steam methane reforming with CO₂ capture. *Energy Convers Manage* 2022;274:116458. <https://doi.org/10.1016/j.enconman.2022.116458>.
- [31] Saha P, Akash FA, Shovon SM, Monir MU, Ahmed MT, Hossain Khan MF, Sarkar SM, Islam MK, Hasan MM, Vo D-VN. Grey, blue, and green hydrogen: a comprehensive review of production methods and prospects for zero-emission energy. *Int J Green Energy* 2024;21(6):1383–97. <https://doi.org/10.1080/15435075.2023.2244583>.
- [32] Dehimi L, Alioui O, Benguerba Y, Yadav KK, Bhutto JK, Fallatah AM, Shukla T, Alreshidi MA, Balsamo M, Badawi M, Erto A. Hydrogen production by the water-gas shift reaction: a comprehensive review on catalysts, kinetics, and reaction mechanism. *Fuel Process Technol* 2025;267:108163. <https://doi.org/10.1016/j.fuproc.2024.108163>.
- [33] Krishnan S, Kamyab H, Nasrullah M, Wahid ZA, Yadav KK, Reungsang A, Chairaprat S. Recent advances in process improvement of dark fermentative hydrogen production through metabolic engineering strategies. *Fuel* 2023;343: 127980. <https://doi.org/10.1016/j.fuel.2023.127980>.
- [34] Guellout Z, Francois-Lopez E, Benguerba Y, Dumas C, Yadav KK, Fallatah AM, Pugazhendhi A, Ernst B. Dark fermentative biohydrogen production from vinicultural biomass without exogenous inoculum in a semi-batch reactor: a kinetic study. *J. Environ. Manage.* 2022;305:114393. <https://doi.org/10.1016/j.jenvman.2021.114393>.
- [35] Luo H, Barrio J, Sunny N, Li A, Steier L, Shah N, Stephens IEL, Titirici MM. Progress and perspectives in photo- and electrochemical-oxidation of biomass for sustainable chemicals and hydrogen production. *Adv Energy Mater* 2021;11(43): 2101180. <https://doi.org/10.1002/aenm.202101180>.
- [36] Tucker-Quinón AM, Rivadeneira-Mendoza BF, Gorozabel-Mendoza ML, Pérez-Almeida IB, García-Guerrero AJ, Dueñas-Rivadeneira AA, Yadav KK, Zambrano-Intriago LA, Rodríguez-Díaz JM. Challenges and potential of layered double hydroxides as electrocatalytic materials for hydrogen production from water: a review of recent advances and applications. *Energy Nexus* 2025;17:100399. <https://doi.org/10.1016/j.nexus.2025.100399>.
- [37] Tashie-Lewis BC, Nnabuife SG. Hydrogen production, distribution, storage and power conversion in a hydrogen economy-a technology review. *Chem Eng J Adv* 2021;8:100172. <https://doi.org/10.1016/j.cej.2021.100172>. ISSN 2666-8211.
- [38] Moradi R, Groth KM. Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis. *Int J Hydrogen Energy* 2019;44(23):12254–69. <https://doi.org/10.1016/j.ijhydene.2019.03.041>.
- [39] Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. *Int J Hydrogen Energy* 2017;42(11):7254–62. <https://doi.org/10.1016/j.ijhydene.2016.03.178>.
- [40] Almansoori A, Shah N. Design and operation of a future hydrogen supply chain: multi-period model. *Int J Hydrogen Energy* 2009;34(19):7883–97. <https://doi.org/10.1016/j.ijhydene.2009.07.109>.
- [41] Reu M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: a flexible hydrogen supply chain model. *Appl Energy* 2017;200:290–302. <https://doi.org/10.1016/j.apenergy.2017.05.050>.
- [42] Zhao S, Wang W, Li Y, Liu C. Pipeline transportation strategy and key technological breakthroughs for high-quality development of hydrogen energy industry under the dual carbon goals. *J Pipeline Sci Eng* 2025:100391. <https://doi.org/10.1016/j.jpse.2025.100391>.
- [43] Apostolou D, Xydis G. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renew Sustain Energy Rev* 2019;113:109292. <https://doi.org/10.1016/j.rser.2019.109292>.
- [44] Uok MD. Advancing sustainable transport: renewable energy integration in hydrogen refueling stations. *Renew Sustain Energy Rev* 2026;226:116393. <https://doi.org/10.1016/j.rser.2025.116393>. ISSN 1364-0321.
- [45] Kurtz J, Sprick S, Bradley TH. Review of transportation hydrogen infrastructure performance and reliability. *Int J Hydrogen Energy* 2019;44(23):12010–23. <https://doi.org/10.1016/j.ijhydene.2019.03.027>.
- [46] Kountouris I, Bramstoft R, Madsen T, Gea-Bermudez J, Munster M, Keles D. A unified european hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. *Nat Commun* 2024;15(1):5517. <https://doi.org/10.1038/s41467-024-49867-w>.
- [47] Ishraque MF, Rahman A, Ahmad K, Shezan SA, Hossain MM, Al Ahmed SR, Arafat MI, Nahid Bintu NE. Derivative free and dispatch algorithm-based optimization and power system assessment of a biomass-PV-hydrogen storage-grid hybrid renewable microgrid for agricultural applications. *Energy Eng* 2025; 122(8). <https://doi.org/10.32604/ee.2025.067492>.
- [48] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF, Ashuri T, Krohn J. Hydrogen fuel cell vehicles: current status and future prospect. *Appl Sci* 2019;9(11):2296. <https://doi.org/10.3390/app9112296>.
- [49] Notter DA, Kouravelou K, Karachalios T, Maria K. Daletou, and Nara Tudela Haberland. Life cycle assessment of PEM FC applications: electric mobility and micro-CHP. *Energy Environ Sci* 2015;8(7):1969–85. <https://doi.org/10.1039/C5EE01082A>.
- [50] Jayabal R. Hydrogen energy storage in maritime operations: a pathway to decarbonization and sustainability. *Int J Hydrogen Energy* 2025;109:1133–44. <https://doi.org/10.1016/j.ijhydene.2025.02.207>. ISSN 0360-3199.
- [51] Dincer I, Acar C. A review on potential use of hydrogen in aviation applications. *Int J Sustain Aviat* 2016;2(1):74–100. <https://doi.org/10.1504/ijsa.2016.076077>. ISSN 2050-0467.
- [52] Bleischwitz R, Bader N. Policies for the transition towards a hydrogen economy: the EU case. *Energy Policy* 2010;38(10):5388–98. <https://doi.org/10.1016/j.enpol.2009.03.041>. ISSN 0301-4215.
- [53] Aguilera RF, Inchauspe J. An overview of hydrogen prospects: economic, technical and policy considerations. *Austr J Agric Resour Econ* 2022;66(1): 164–86. <https://doi.org/10.1111/1467-8489.12458>.
- [54] Curcio E. Techno-economic analysis of hydrogen production: costs, policies, and scalability in the transition to net-zero. *Int J Hydrogen Energy* 2025;128:473–87. <https://doi.org/10.1016/j.ijhydene.2025.04.013>. ISSN 0360-3199.
- [55] Strelkovskii N, Komendantova N. Integration of UN sustainable development goals in national hydrogen strategies: a text analysis approach. *Int J Hydrogen Energy* 2025;102:1282–94. <https://doi.org/10.1016/j.ijhyden.2025.01.134>.
- [56] Mongeon P, Paul-Hus A. The journal coverage of web of science and scopus: a comparative analysis. *Scientometrics* 2016;106(1):213–28. <https://doi.org/10.1007/s11192-015-1765-5>.
- [57] Visser M, van Eck NJ, Waltman L. Large-scale comparison of bibliographic data sources: scopus, web of science, dimensions, crossref, and microsoft academic. *Quant Sci Stud* 2021;2(1):20–41. https://doi.org/10.1162/qss_a.00112.
- [58] Baas J, Schotten M, Plume A, Cote G, Karimi R. Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quant Sci Stud* 2020;1(1):377–86. https://doi.org/10.1162/qss_a.00019.
- [59] Aria M, Cuccurullo C. bibliometrix: an R-tool for comprehensive science mapping analysis. *J Informet* 2017;11(4):959–75. <https://doi.org/10.1016/j.joi.2017.08.007>.
- [60] van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 2009;84(2):523–38. <https://doi.org/10.1007/s11192-009-0146-3>.
- [61] Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: an overview and guidelines. *J Bus Res* 2021;133:285–96. <https://doi.org/10.1016/j.jbusres.2021.04.070>.
- [62] Zupic I, Cater T. Bibliometric methods in management and organization. *Organ Res Methods* 2015;18(3):429–72. <https://doi.org/10.1177/1094428114562629>.
- [63] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. <https://doi.org/10.1136/bmj.n71>.
- [64] Richard Landis J, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;33(1):159–74. <https://doi.org/10.2307/2529310>.
- [65] Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas* 1960; 20(1):37–46. <https://doi.org/10.1177/001316446002000104>.
- [66] Tahamtan I, Afshar AS, Ahmadvadeh K. Factors affecting number of citations: a comprehensive review of the literature. *Scientometrics* 2016;107(3):1195–225. <https://doi.org/10.1007/s11192-016-1889-2>.
- [67] Waltman L, van Eck NJ, van Leeuwen TN, Visser MS, van Raan AFJ. Towards a new crown indicator: some theoretical considerations. *J Informet* 2011;5(1): 37–47. <https://doi.org/10.1016/j.joi.2010.08.001>.
- [68] Kessler MM. Bibliographic coupling between scientific papers. *Am Doc* 1963;14(1):10–25. <https://doi.org/10.1002/asi.5090140103>.
- [69] van Eck NJ, Waltman L. How to normalize cooccurrence data? An analysis of some well-known similarity measures. *J Am Soc Inf Sci Technol* 2009;60(8): 1635–51. <https://doi.org/10.1002/asi.21075>.
- [70] Waltman L, van Eck NJ, Noyons ECM. A unified approach to mapping and clustering of bibliometric networks. *J Informet* 2010;4(4):629–35. <https://doi.org/10.1016/j.joi.2010.07.002>.
- [71] Traag VA, Waltman L, van Eck NJ. From Louvain to Leiden: guaranteeing well-connected communities. *Sci Rep* 2019;9:5233. <https://doi.org/10.1038/s41598-019-41695-z>.
- [72] Hunter JD. Matplotlib: a 2d graphics environment. *Comput Sci Eng* 2007;9(3): 90–5. <https://doi.org/10.1109/MCSE.2007.55>.
- [73] Waskom ML. seaborn: statistical data visualization. *J Open Source Softw* 2021;6(60):3021. <https://doi.org/10.21105/joss.03021>.
- [74] Hassan M, Shrabana SS, Islam MA, Basaruddin KS, Ijaz MF, Kamarrudin NSB, Takemura H. Integration of extended reality technologies in transportation systems: a bibliometric analysis and review of emerging trends, challenges, and future research. *Results Eng* 2025;26:105334. <https://doi.org/10.1016/j.rineng.2025.105334>.

- [75] Real R, Vargas JM. The probabilistic basis of Jaccard's index of similarity. *Syst Biol* 1996;45(3):380–5. <https://doi.org/10.1093/sysbio/45.3.380>.
- [76] Newman MEJ, Girvan M. Finding and evaluating community structure in networks. *Phys Rev E* 2004;69(2):026113. <https://doi.org/10.1103/PhysRevE.69.026113>.
- [77] Ellegaard O, Wallin JA. The bibliometric analysis of scholarly production: how great is the impact? *Scientometrics* 2015;105(3):1809–31. <https://doi.org/10.1007/s11192-015-1645-z>.
- [78] Osman AI, Mahmoud Nasr AR, Mohamed AA, Ayati A, Farghali M, Al-Muhtaseb AH, Al-Fatesh AS, Rooney DW. Life cycle assessment of hydrogen production, storage, and utilization toward sustainability. *Wiley Interdiscip Rev: Energy Environ* 2024;13(3):e526. <https://doi.org/10.1002/wene.526>.
- [79] Fayyazi M, Sardar P, Thomas SI, Daghigh R, Jamali A, Esch T, Kemper H, Langari R, Khayyam H. Artificial intelligence/machine learning in energy management systems, control, and optimization of hydrogen fuel cell vehicles. *Sustainability* 2023;15(6):5249. <https://doi.org/10.3390/su15065249>. ISSN 2071-1050.
- [80] Chakraborty S, Dash SK, Elavarasan RM, Kaur A, Elangovan D, Meraj ST, Kasinathan P, Said Z. Hydrogen energy as future of sustainable mobility. *Front Energy Res* 2022;10:893475. <https://doi.org/10.3389/fenrg.2022.893475>.
- [81] Wei S, Liu Y, Sha X, Peng W. Hydrogen policy evolution in China and globally: a spatial and thematic comparison. *Renew Sustain Energy Rev* 2025;224:116087. <https://doi.org/10.1016/j.rser.2025.116087>.
- [82] Rasel Ahmed M, Nimul Hasan M, Sk A, Shezan M, Ishraque F, Das BK, et al. Assessment of a grid-connected microgrid for suburban areas and EV loads with battery storage during planned grid outages using DigSILENT powerfactory. *Electr Eng* 2025;107:15069–98. <https://doi.org/10.1007/s00202-025-03313-2>.
- [83] Shezan SA, Ishraque MF, Ahmad K, Hasan MN, Shafiullah GM, Rahman MM. Performance evaluation of constant voltage and reactive power control strategies for renewable-integrated grid-connected EV charging stations. *IEEE Trans Ind Appl* 2025;61(6):8712–21. <https://doi.org/10.1109/tia.2025.3576748>.
- [84] Gray N, O'Shea R, Wall D, Smyth B, Lens PNL, Murphy JD. Batteries, fuel cells, or engines? A probabilistic economic and environmental assessment of electricity and electrofuels for heavy goods vehicles. *Adv Appl Energy* 2022;8:100110. <https://doi.org/10.1016/j.adapen.2022.100110>.
- [85] Cullen DA, Neyerlin KC, Ahluwalia RK, Mukundan R, More KL, Borup RL, et al. New roads and challenges for fuel cells in heavy-duty transportation. *Nat Energy* 2021;6:462–74. <https://doi.org/10.1038/s41560-021-00775-z>.
- [86] Krishnan S, Koning V, Theodorus M, de Groot A, de Groot P, Mendoza G, Junginger M, Kramer GJ. Present and future cost of alkaline and PEM electrolyser stacks. *Int J Hydrogen Energy* 2023;48(83):32313–30. <https://doi.org/10.1016/j.ijhydene.2023.05.031>.
- [87] Aminaho EN, Aminaho NS, Aminaho F. Techno-economic assessments of electrolyzers for hydrogen production. *Appl Energy* 2025;399:126515. <https://doi.org/10.1016/j.apenergy.2025.126515>.
- [88] Navinkumar TM, Bharatiraja C. Sustainable hydrogen energy fuel cell electric vehicles: a critical review of system components and innovative development recommendations. *Renew Sustain Energy Rev* 2025;215:115601. <https://doi.org/10.1016/j.rser.2025.115601>.
- [89] Bhuiyan MMH, Siddique Z. Hydrogen as an alternative fuel: a comprehensive review of challenges and opportunities in production, storage, and transportation. *Int J Hydrogen Energy* 2025;102:1026–44. <https://doi.org/10.1016/j.ijhydene.2025.01.033>.
- [90] Mori M, Iribarren D, Cren J, Cor E, Lotrić A, Gramc J, Drobnic B, Rey L, Carriedo F, Puig-Samper G, Bargiacchi E, Dufour J, Stropnik R. Life cycle sustainability assessment of a proton exchange membrane fuel cell technology for ecodesign purposes. *Int J Hydrogen Energy* 2023;48(99):39673–89. <https://doi.org/10.1016/j.ijhydene.2023.05.255>.
- [91] Mvokwe SA, Oyediji OO, Agoro MA, Meyer EL, Rono N. A critical review of the hydrometallurgy and pyrometallurgical recovery processes of platinum group metals from end-of-life fuel cells. *Membranes* 2025;15(1):13. <https://doi.org/10.3390/membranes15010013>.
- [92] Dirkes S, Leidig J, Fisch P, Pischinger S. Prescriptive Lifetime Management for PEM fuel cell systems in transportation applications, Part I: State of the art and conceptual design. *Energy Convers Manage* 2023;277:116598. <https://doi.org/10.1016/j.enconman.2022.116598>.
- [93] Luo Y, Yinghong W, Li B, Jingkui Q, Feng S-P, Chu PK. Optimization and cutting-edge design of fuel-cell hybrid electric vehicles. *Int J Energy Res* 2021;45(13):18392–423. <https://doi.org/10.1002/er.7094>. ISSN 0363-907X.
- [94] Naanani H, Nachtane M, Faik A. Advancing hydrogen safety and reliability through digital twins: applications, models, and future prospects. *Int J Hydrogen Energy* 2025;115:344–60. <https://doi.org/10.1016/j.ijhydene.2025.02.440>.
- [95] Bhavana GB, Anand R, Ramprabhakar J, Meena VP, Jadoun VK, Benedetto F. Applications of blockchain technology in peer-to-peer energy markets and green hydrogen supply chains: a topical review. *Sci Rep* 2024;14(1):21954. <https://doi.org/10.1038/s41598-024-72642-2>. ISSN 2045-2322.
- [96] Shan R, Kittner N. Sector-specific strategies to increase green hydrogen adoption. *Renew Sustain Energy Rev* 2025;214:115491. <https://doi.org/10.1016/j.rser.2025.115491>. ISSN 1364-0321.
- [97] Andrade P, Laadjal K, Alcaso AN, Cardoso AJM. A comprehensive review on condition monitoring and fault diagnosis in fuel cell systems: challenges and issues. *Energies* 2024;17(3):657. <https://doi.org/10.3390/en17030657>.
- [98] Mahbub Hassan M, Kabir E, Jusoh M, An HK, Negnevitsky M, Li C. Large language models in transportation: a comprehensive bibliometric analysis of emerging trends, challenges and future research. *IEEE Access* 2025. <https://doi.org/10.1109/access.2025.3589319>. ISSN 2169-3536.
- [99] Celsi MR, Celsi LR. Quantum computing as a game changer on the path towards a net-zero economy: a review of the main challenges in the energy domain. *Energies* 2024;17(5):1039. <https://doi.org/10.3390/en17051039>.
- [100] Ryu H, Lee D, Shin J, Song M, Lee S, Kim H, et al. A web-based decision support system (DSS) for hydrogen refueling station location and supply chain optimization. *Int J Hydrogen Energy* 2023;48(93):36223–39. <https://doi.org/10.1016/j.ijhydene.2023.06.064>.
- [101] Folgado FJ, González I, Calderón AJ. Data acquisition and monitoring system framed in industrial internet of things for PEM hydrogen generators. *Internet of Things* 2023;22:100795. <https://doi.org/10.1016/j.iot.2023.100795>. ISSN 2542-6605.
- [102] Yavari A, Harrison CJ, Gorji SA, Shafiei M. Hydrogen 4.0: a cyber-physical system for renewable hydrogen energy plants. *Sensors* 2024;24(10):3239. <https://doi.org/10.3390/s24103239>. ISSN 1424-8220.
- [103] Ma H, Yang L, Kou Z, Xue Z, Wei Y, Zhang K, Deng P, Di C, Zhu Y, Wang H. Cybersecurity and cyber-attacks in the growing natural gas and hydrogen industry: a systematic review of challenges and opportunities. *Gas Sci Eng* 2025;205744. <https://doi.org/10.1016/j.jgsce.2025.205744>. ISSN 2949-9089.
- [104] Feng Z, Luo Y, Li D, Pan J, Tan R, Chen Y. Integrating digital twins and machine learning for advanced control in green hydrogen production. *Chain* 2025;2(1):1–14. <https://doi.org/10.23919/chain.2025.000003>.
- [105] Alsharif S, Huxoll N, Wibbeke J, Grimm T, Brand M, Lehnhoff S. Digital twin concept and architecture for fleets of hydrogen electrolyzers. *Front Energy Efficiency* 2024;2:1437214. <https://doi.org/10.3389/fenef.2024.1437214>.
- [106] Alshehhi HH, Hummieda A, Musamih A, Chadly A, Salah K, Mayyas A. Blockchain-based traceability and certifications of hydrogen refueling station components. *Clean Eng Technol* 2025;101104. <https://doi.org/10.1016/j.clet.2025.101104>.