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Dynamic evolution and frontiers of energy decentralization research: A bibliometric-based review

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ABSTRACT

Energy decentralization signifies a fundamental shift in energy production and governance from conventional, centralized systems towards distributed, localized, and end-user-centric paradigms. This transition is of paramount importance for advancing energy efficiency and bolstering energy security. Employing bibliometric analysis and literature review methodologies, we utilize CiteSpace to delineate the intellectual landscape, research hotspots, and evolutionary trends within the energy decentralization literature from 2008 to 2024, based on the Web of Science (WoS) core collection. Our analysis reveals that: ①Robust collaborative networks exist at the international and institutional levels, while scholars tend to form distinct collaborative clusters. China, USA, and Denmark emerge as prominent contributors to the field. ②The research landscape is thematically diverse, with focal points on emerging technology applications, energy management and optimization, and energy governance and institutional arrangements. ③Prospectively, future research is poised to concentrate on the coordination mechanisms between technology diffusion and institutional alignment, the trade-off between community energy expansion and distributive justice, and the interplay between energy system resilience and governance constraints. The dynamic knowledge map constructed herein provides a scientific foundation for understanding the academic trajectory of the energy decentralization field and for identifying promising avenues for future research.

1. Introduction

Amid the accelerating global energy transition, energy systems are undergoing a structural reshaping from conventional "centralized" paradigms toward "decentralized" configurations [1]. This transformation entails not merely a physical relocation of infrastructure from large-scale power plants to distributed nodes, but a fundamental paradigm shift in the logic of energy production and management. While decentralized deployment significantly enhances system flexibility, resilience, and resource allocation efficiency, it also introduces profound challenges. The intermittency of renewable energy and the impact of net load fluctuations—exemplified by the "duck curve"—impose substantial pressure on system stability and market mechanisms [2]. Consequently, energy decentralization has transcended the scope of a purely technological domain, evolving into a complex strategic imperative that encompasses system optimization, institutional restructuring, and social governance [3,4]. Deciphering the evolutionary logic of the phenomenon is therefore crucial for grasping the multidimensional drivers of the ongoing energy transition.

Scholarly discourse on energy decentralization spans diverse disciplines, yet analytical foci remain significantly distinct across fields. In the realm of engineering and power systems, research predominantly targets technological dimensions, such as distributed energy resources (DERs), microgrids, and virtual power plants (VPPs), focusing on their implications for system operation and dispatch efficiency [5–8]. Conversely, energy economics and policy literature scrutinizes institutional aspects, centering on market design, regulatory adaptation, and incentive mechanisms for prosumers [9,10]. Meanwhile, social and governance studies emphasize the human dimension, exploring community energy practices, social acceptance, and multi-level governance arrangements [11,12]. Despite sectoral deepening, the literature exhibits characteristics of disciplinary fragmentation and siloed research trajectories. As a result, "energy decentralization", as an integrated unit of analysis lacks a systematic mapping of its knowledge structure. Existing reviews struggle to provide a holistic panorama of the field's academic landscape: What global collaboration networks have emerged

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globally? How has the research gravity shifted and interacted among the technical, institutional, and social dimensions over time? Which themes constitute the field's intellectual core, or are evolving into new frontiers?

To bridge these gaps, we employ bibliometric and visualization analysis to systematically review the literature on energy decentralization from 2008 to 2024. This approach aims to reveal the field's holistic knowledge structure and evolutionary logic. Our primary contributions are reflected in the following three aspects: (1) By treating "energy decentralization" as an overarching analytical subject, we systematically map its interdisciplinary landscape, providing a comprehensive perspective for understanding the structural transformation of energy systems. (2) We elucidate the dynamic migration of research focus across technical, institutional, and societal dimensions, uncovering the phased characteristics of these shifts through the analysis of collaboration networks and thematic evolution. (3) We identify critical core issues and emerging frontiers, offering a scientific reference for future theoretical integration and policy formulation in areas such as energy governance, market design, and social adaptation.

2. Research design

2.1. Concept definition

The concept of energy decentralization originated in engineering and power system research, initially describing the evolution of power systems from vertically integrated, centralized hierarchies toward geographically dispersed, locally dispatchable DERs and microgrids [13–15]. Within this early paradigm, theoretical discourse primarily

Table 1
Concepts and core definition of energy decentralization in existing literature.

Article	Author	Year	Focus dimension	Core definition/Concept
Distributed generation technologies, definitions and benefits	El-Khattam Salama	2004	Technical (distributed generation technology and system architecture)	Distributed generation is defined as power generation units located near the load side and independent of the main grid. Its core "decentralization" characteristic lies in the shift of generation capacity from centralized large-scale power plants to geographically dispersed, locally accessible energy resources.
Overview of control, integration and energy management of microgrids	Li Nejabatkhah	2014	Technical (microgrid control, system integration)	Microgrids are regarded as locally controlled energy systems, with their "decentralization" nature manifested in the following: the power system decouples from large-scale hierarchical control structures, transitioning toward "autonomous energy supply units" composed of local renewable energy sources and energy storage.
Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance	Von Wirth Gislason Seidl	2018	Societal (community-level autonomy, social acceptance, local community)	Defining neighborhood-scale distributed energy systems as locally deployed and shared energy configurations within communities, their "decentralization" nature manifests in the following ways: decision-making authority over energy, cost-sharing arrangements, and benefit distribution are all established at the community level, thereby diminishing the dominant role of central utilities in both technical implementation and governance.
Decentralized energy, decentralized accountability? Lessons on how to govern decentralized electricity transitions from multi-level natural resource governance	Brisbois	2020	Institutional (multi-tiered governance, accountability structure, decentralized oversight)	Viewing "decentralization" as a multi-tiered governance transformation, within this framework, the dispersion of technology and assets serves only as the foundation. The crux lies in redistributing governance responsibilities, regulatory authority, and decision-making processes from central institutions to local governments, communities, and users. This creates a "decentralized governance" structure that expands both horizontally and vertically.
Taking the car out of the countryside: Understanding opposition to climate policy in rural Finland	Heiskanen Matschoss Rinkinen et al.	2024	Societal (social acceptance, behavioral resistance, local context)	Regarding "decentralization" as the devolution of energy governance authority to local and community levels, emphasizing social acceptance, local autonomy, and community control over energy choices.
A critical review of distribution system planning: Optimal placement and sizing of distributed generation and energy storage devices in microgrids	Malika Pattanaik Panda et al.	2025	Technical (distributed resource planning, configuration optimization)	Planning and optimizing distributed power generation and energy storage represents a key technical pathway for decentralizing power systems. Its "decentralization" nature lies in the spatial proximity of distributed resources to load points, structurally reducing reliance on large-scale centralized generation.
Peer-to-peer energy trading of solar and energy storage: A networked multiagent reinforcement learning approach	Feng Liu	2025	Institutional/Market (P2P trading mechanism, decentralized market structure)	Treating distributed photovoltaics and energy storage as independent market entities, peer-to-peer (P2P) transactions form a decentralized trading structure that bypasses central retailers. This "decentralization" fundamentally shifts energy from centralized pricing mechanisms to direct bilateral interactions between producers and consumers.
Bridging theory and practice: A comprehensive review of virtual power plant technologies and their real-world applications	Esfahani Alizadeh Cao et al.	2025	Technical/Institutional (institutionalization of VPPs's technical architecture and dispatch mechanisms)	VPPs is defined as a coordinated platform integrating DERs. Its "decentralization" nature lies in enabling numerous small-scale resources to participate in the electricity market through "virtual aggregation"—physically dispersed yet operationally independent of central power plants.
Asymmetric Nash bargaining-based community-centric energy sharing strategy for numerous prosumers	Yu Xu Chen et al.	2025	Institutional/Societal (community energy sharing, producer-consumer interaction)	Defining energy sharing as a locally negotiated mechanism for redistributing energy within communities, its "decentralization" nature manifests as follows: authority over energy allocation shifts from grid operators to communities and prosumer collectives.

Note: This table highlights the primary analytical dimensions of energy decentralization. The quantitative analysis is based strictly on WoS data (2008–2024); selected recent articles are included for conceptual purposes only.

revolved around the reconfiguration of physical infrastructure. The objective was to mitigate the intermittency and uncertainty of renewable energy by minimizing transmission distances and enhancing local operational flexibility. However, as digital technologies, market mechanisms, and diverse forms of social participation permeate energy systems, the connotation of energy decentralization has rapidly transcended its engineering origins. It has evolved into a comprehensive systemic transformation encompassing technological deployment, institutional restructuring, and social governance reform [16–21] (see Table 1 for a systematic overview).

Specifically, existing literature characterizes the multidimensional nature of energy decentralization. (1) From the technical dimension, studies focus on how distributed energy resources, energy storage, microgrids, and VPPs reshape the physical structure and operations of energy systems. The core of this dimension is the transition from centralized supply to multi-node coordination. (2) From the institutional dimension, regarding the institutional dimension, the research focus shifts to adjustments in market design, pricing mechanisms, grid access rules, and regulatory frameworks. This strand emphasizes how institutional innovations empower prosumers, aggregators, and local energy units to participate in resource allocation and market trading with reduced reliance on centralized dispatch. (3) From the societal dimension, energy decentralization is examined within the contexts of multi-level governance and local conditions. This research addresses issues of social acceptance, accountability, and equity arising from the devolution of decision-making power to local governments, communities, and end-users. Building on these strands of literature, we define energy decentralization as a systemic evolutionary process in the context of energy transition. In this process, the deployment of distributed technologies, the restructuring of institutional and market mechanisms, and the adjustment of governance levels facilitate the diffusion of production, dispatch, and decision-making powers from centralized entities to diverse actors and local levels. This definition underscores that decentralization is not merely a singular technical choice or governance model, but a comprehensive transition driven by the interplay of technical, institutional, and social mechanisms. This framework provides a rigorous basis for delineating the scope of this review: First, we exclude narrowly defined techno-centric literature—specifically, studies focusing solely on physical attributes such as storage materials, control algorithms, or photovoltaic module efficiency without addressing system-level dispatch, market mechanisms, or governance implications. Second, we incorporate literature on institutional and contextual governance—covering policy, market design, regulatory models, and community ownership—provided the analysis addresses the downward shift of power structures, incentive mechanisms, or decision-making hierarchies within the "energy decentralization".

2.2. Data sources and search strategy

Adhering to established bibliometric protocols, we utilized the Web of Science (WoS) Core Collection as our primary data source [22,23]. Recognized as a premier citation indexing platform, WoS features a stable data structure and extensive coverage of high-impact peer-reviewed journals, rendering it a robust foundation for conducting globally representative literature analyses [24,25]. To ensure a comprehensive, multidisciplinary examination of energy decentralization, our dataset encompasses the Science Citation Index Expanded (SCI-E), the Social Sciences Citation Index (SSCI), and the Arts & Humanities Citation Index (AHCI), spanning the timeframe from 2008 to 2024. To operationalize our definition of energy decentralization as a multidimensional transformation—spanning technological, institutional, and societal domains—we constructed a corresponding three-tiered Boolean search strategy. As detailed in Table 2, specific keyword clusters were linked using the "AND" operator. The search parameters targeted the WoS "Topic" field, which retrieves terms from titles, abstracts, and keywords.

Table 2
Literature search keywords classification list.

Group (Logic layer)	Conceptual focus	Keyword clusters
Subject & Core	Core concepts and direct subject	"energy decentralization" OR "decentralized energy" OR "energy system decentralization" OR "distributed energy resources" OR "DER" OR "distributed generation" OR "DG" OR microgrid* OR "local energy system" OR "community energy" OR "peer-to-peer energy" OR "P2P energy"
Dimensional Constraint	Multidimensional manifestations (technical, institutional, and societal)	"energy governance" OR "energy policy" OR "regulatory framework" OR "energy regulation" OR "market design" OR "market mechanism" OR "power market reform" OR "market liberalization" OR "deregulation" OR "energy storage" OR "demand response" OR "smart grid" OR "digital energy" OR "VPP" OR "transactive energy" OR "virtual power plant" OR "energy justice" OR "energy equity" OR "social acceptance" OR "public participation" OR "community engagement"
Contextual Refinement	Contextual and scope qualifiers	"decentraliz*" OR "distributed" OR "local" OR "multi-level governance" OR "polycentric governance" OR "community ownership" OR "community management" OR "bottom-up" OR "prosumption" OR "prosumer*" OR "energy sharing" OR "local generation"

2.3. Methods

2.3.1. Data collection and refinement

The data retrieval and screening protocol follows the flowchart depicted in Fig. 1. An initial keyword search yielded 11,384 records. After applying automated filters for document type, language, and publication timeframe, a preliminary set of 9420 documents was obtained. Subsequently, a manual review of titles, abstracts, and keywords was conducted for each entry. Theoretical consistency was calibrated against the tri-dimensional conceptual framework of "technical-institutional-societal", resulting in a final corpus of 6182 retained articles. Exclusions primarily targeted highly techno-centric studies, such as micro-level physicochemical analyses of storage media, capacity optimization for renewable storage, and data-driven scheduling algorithms. While these studies possess significant engineering value, their analytical frameworks generally lack engagement with core decentralization themes—specifically, the restructuring of power dynamics, market mechanisms, community empowerment, or policy adaptation.

2.3.2. Analysis methods

We adopt a synergistic methodological approach combining systematic literature review, bibliometric analysis, content analysis, and knowledge mapping. First, the Systematic Literature Review method is employed to comprehensively execute the collection and screening of relevant literature. This rigorous approach not only facilitates the construction of the field's knowledge inventory but also provides a detailed reflection of its status quo and developmental trajectory [26]. Second, Bibliometric Analysis and Content Analysis are utilized to scrutinize the corpus across multiple dimensions, including temporal trends,

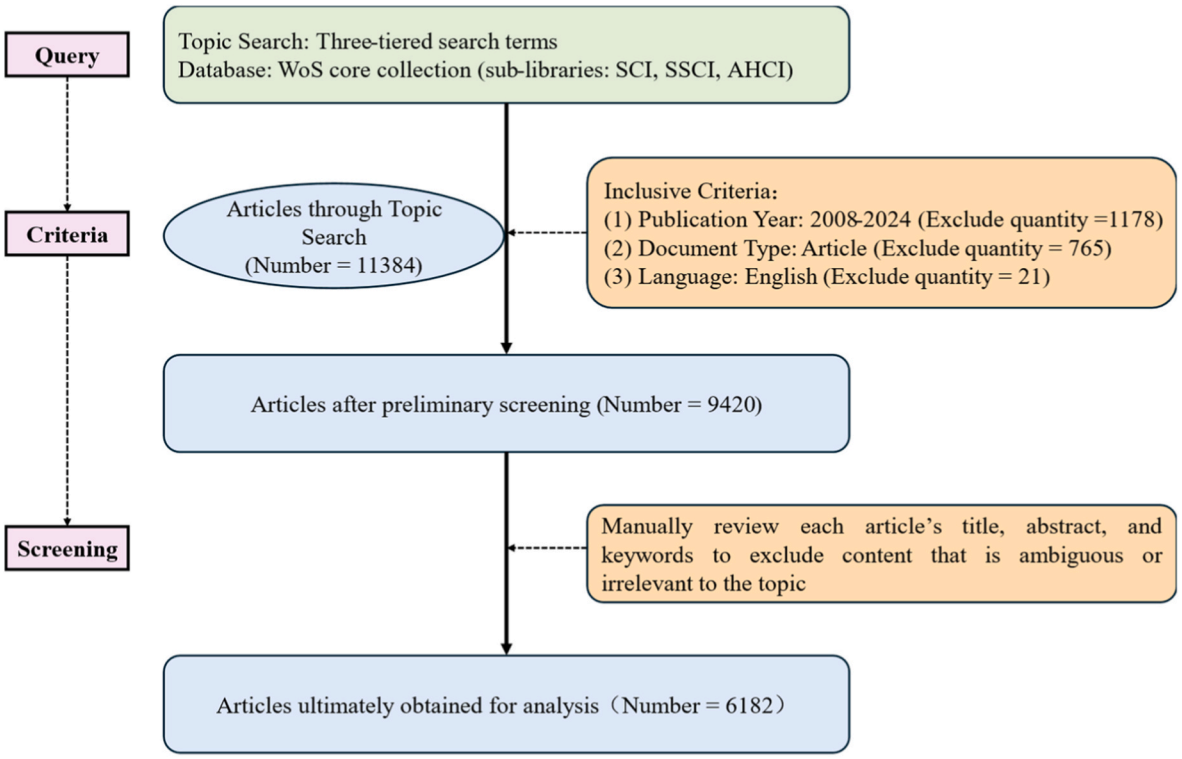


Fig. 1. Research framework for bibliometric analysis.

geographical distribution, academic collaboration, and keyword evolution. Bibliometrics offers a quantitative lens to delineate scientific dynamics and academic progress within a specific discipline [27]. Complementarily, content analysis systematically interprets textual data to extract qualitative and quantitative insights regarding specific themes or phenomena [28].

To visualize the analytical results, we employ knowledge mapping techniques. By integrating scientometric data with visual representation, knowledge maps effectively unveil the intricate interrelationships and influence patterns among research topics, scholars, and disciplines. We select CiteSpace to map the intellectual landscape, visualizing disciplinary trends, identifying research hotspots, and assessing the impact of scholarly contributions. Through this integrated methodology, we aim to provide a comprehensive and profound perspective for understanding and assessing the research dynamics and future trends in energy decentralization.

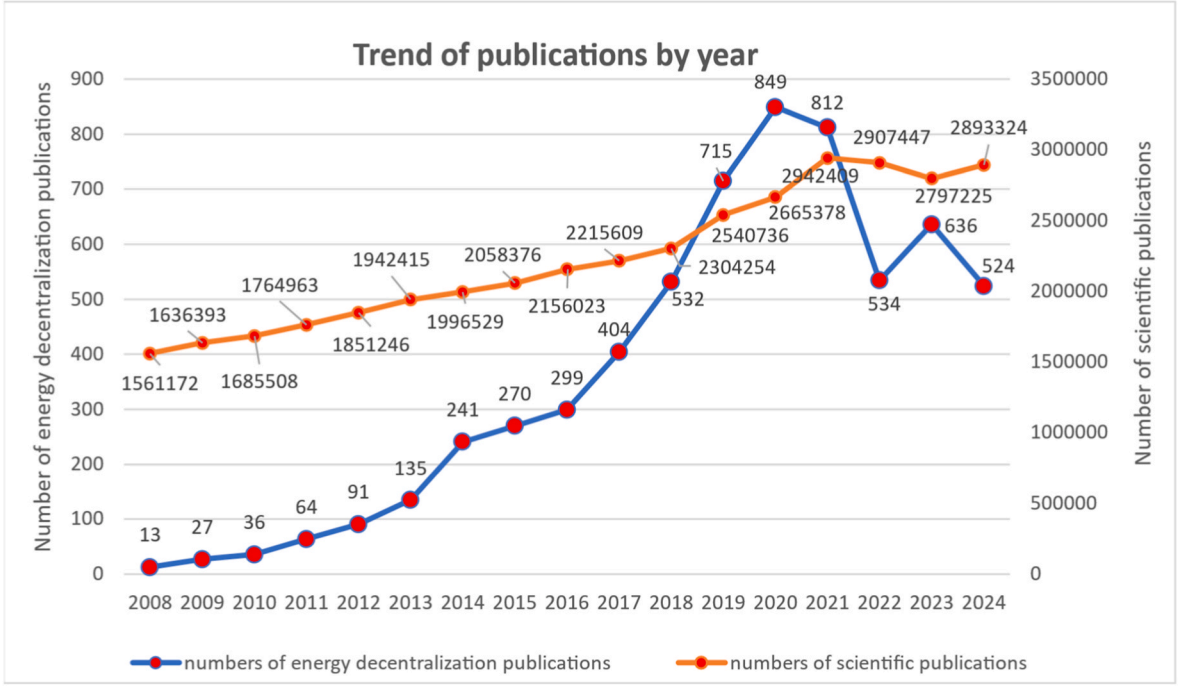


Fig. 2. Annual variation in the number of publications.

3. Bibliometric analysis

3.1. Publication trend analysis

To examine annual changes in energy decentralization research, we present a temporal trend graph (Fig. 2). As shown in the graph, after an initial period of consolidation, this sector reached a pivotal turning point in 2014 (with a peak growth rate of 78.52%) and maintained rapid expansion until hitting its historical high in 2020. This phase of explosive growth stems from dual drivers at both macro and micro levels: On one hand, international policy frameworks like the Paris Agreement have anchored institutional expectations for research on the low-carbon transition. Specifically, the European Union's "Clean Energy for All Europeans" package significantly legitimized the status of prosumers, directly catalyzing a surge of research on energy community governance. Similarly, China's "Dual Carbon" goals provide strong institutional endorsement for the large-scale deployment of distributed systems. On the other hand, the continuous decline in costs for renewable energy technologies such as photovoltaics has propelled the gradual realization of grid parity, enabling energy decentralization to transition from policy-driven pilot projects to large-scale adoption on the consumer side. Throughout the entire cycle, the number of papers published in this field has followed an overall trajectory of "rapid growth followed by high-level fluctuations". Its early and mid-period growth rates significantly exceeded the average for global scientific publications during the same period, highlighting the central role of energy decentralization as a core issue in energy transition research.

3.2. Collaboration networks and scholarly contributions

To accurately assess the scholarly contributions and collaborative patterns of countries and regions, institutions, and authors in energy decentralization research, we draw on the practices of existing studies [29,30]. We select multiple core indicators for quantitative analysis and utilize knowledge mapping to visualize the distributional structure and collaborative linkages among research entities.

3.2.1. Country and region analysis

According to the sample literature, we construct a national collaboration network diagram comprising 108 nodes (Fig. 3). The figure reveals that energy decentralization research has formed a tightly connected collaborative network, with increasingly frequent transnational knowledge flows. Among these, France (0.19), India (0.16), USA (0.15), and Denmark (0.12) exhibit high centrality, serving as "knowledge hubs" within the global research network. They play an irreplaceable intermediary role in facilitating cross-regional technology transfer and multilateral cooperation.

Table 3 further reveals the specific contribution characteristics of high-output countries. China leads in research output, primarily driven by the practical demands of its large-scale infrastructure development. Guided by the "ultra-high voltage & distributed generation" strategy, Chinese research is highly concentrated on technical implementation aspects such as microgrid control, algorithm optimization, and blockchain-based P2P transactions, demonstrating a distinct engineering application orientation [31,32]. Regarding transition pathways, this line of research characterizes the process as an "embedded expansion", where distributed technologies are integrated into existing centralized regimes. Consequently, international collaborations in this domain tend to prioritize engineering-oriented issues, such as technical feasibility and system performance. In contrast, research in USA and Denmark is deeply rooted in a tradition of market liberalization. Focusing on the reconfiguration of production relationships within the energy system, these studies delve into transactive energy architectures, demand

Table 3
Top ten countries and regions by publication volume.

Rank	Country	TP	TC	ACPP	SP (%)
1	China	1563	66516	42.56	45.11%
2	USA	1118	71312	63.79	51.16%
3	Iran	659	30230	45.87	47.95%
4	England	408	20880	51.18	71.81%
5	Australia	404	21337	52.81	56.93%
6	India	382	12213	31.97	30.89%
7	Italy	332	14480	43.61	53.31%
8	Canada	328	21764	66.35	54.27%
9	Spain	301	14437	47.96	47.84%
10	Denmark	292	19599	67.12	86.30%

Note: Total Papers (TP) reflects the number of all papers published by a given researcher or team in a given time period; Total Citations (TC) represents the total number of times a paper has been cited (including self-citations); Average Citations per Publication (ACPP) is the ratio of TC to TP, reflecting the average academic impact per unit of output; Share of Publications (SP) measures the percentage of collaborative papers of a given research subject out of its total papers.

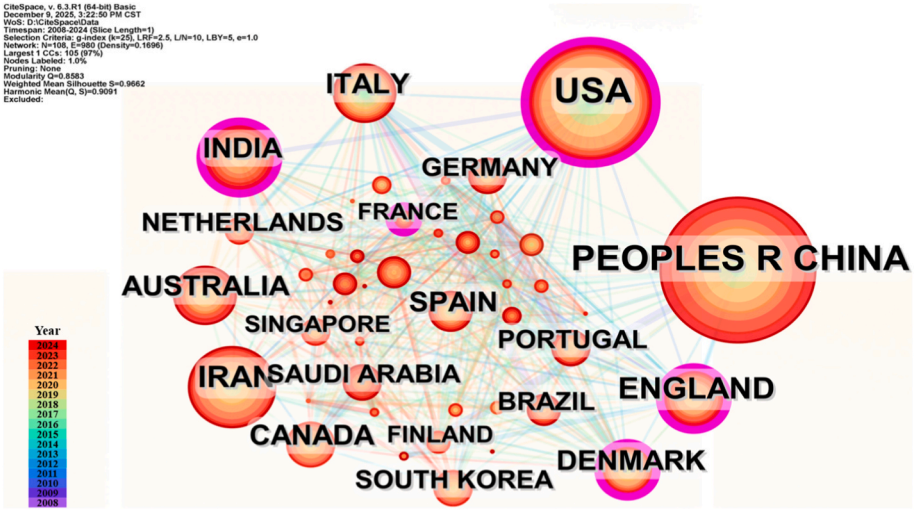


Fig. 3. Country collaboration network. Note: The node labels in the figure indicate countries. The size of the node and label font indicates the number of articles published by the country. For the convenience of analysis, the threshold range is set: When the frequency of country collaboration ≥20, the label is shown in the figure. The linked lines of the nodes represent the existence of cooperation between countries. The color of the linking line denotes the time of the first collaboration between countries. The nodes with purple outer circles indicate their intermediary centrality.

response strategies, and game-theoretic market mechanisms [33–35]. This focus on top-level design and universal principles makes its research findings more readily accepted by the international academic community, thereby achieving greater international collaboration and influence.

3.2.2. Institution analysis

We extract 289 core institutional nodes most representative of this field using the CiteSpace algorithm, constructing an institutional co-occurrence map comprising 1199 collaborative connections (Fig. 4). From an organizational perspective, research universities serve as the core entities. Concurrently, government agencies such as the United States Department of Energy (DOE) and enterprises like State Grid Corporation of China occupy pivotal positions within the institutional collaboration network. This indicates that energy decentralization research has progressively evolved into a collaborative "industry-academia-research" framework involving universities, government departments, and industrial entities.

We further identify the institutions playing a dominant role in the aforementioned network, as shown in Table 4. China exhibits a distinct "deployment-driven" characteristic. State Grid Corporation of China leads with 204 published documents, alongside three universities occupying four spots in the top ten. This unique "central enterprise-led" pattern profoundly reflects China's logic of driving transformation through massive infrastructure projects such as ultra-high voltage transmission and distribution network upgrades. European and American institutions have established their discourse authority through a "mechanism design orientation". Although DOE and Aalborg University are slightly smaller in scale, they occupy the academic high ground due to their exceptionally high ACPP. This reflects their dominance in microgrid standardization, market rule design, and the macro-theoretical construction of "smart energy systems", focusing on addressing the replicability of decentralized models across different institutional environments.

3.2.3. Author analysis

To characterize the knowledge-producing agents and their collaborative structures in decentralized energy research, we construct an author collaboration network (Fig. 5). Overall, this field exhibits a network characteristic of "relatively concentrated core scholars and highly dispersed peripheral authors". Early research primarily focuses on fundamental operational issues of distributed generation and microgrids, emphasizing core engineering topics such as system stability, energy storage optimization, and advanced control architectures [36–38]. As time progressed into the mid-term phase, the network architecture exhibited characteristics of multiple coexisting cores and enhanced horizontal interconnections. The research focuses gradually shifted from system-level stability issues to multi-agent coordination and user-side participation [39–41]. This suggests that certain technological niches have begun to interact with established electricity regimes and market rules, broadening the research agenda from purely engineering issues to dispatch mechanisms and behavioral responses. Consequently, this shift has attracted new cohorts of authors into the research network. The red nodes that emerge later at the network periphery and in certain core areas exhibit high-density cluster-like structures. This phase further extends energy decentralization research into complex systems, uncertainty management, and novel application scenarios [42–44]. Within the Multi-Level Perspective (MLP)

Table 4
Institutions in the top 10 in terms of number of publications.

Rank	Institution	TP	TC	ACPP	Country
1	State Grid Corporation of China	204	6390	31.32	China
2	United States Department of Energy (DOE)	190	14658	77.15	USA
3	Aalborg University	165	13651	82.73	Denmark
4	Islamic Azad University	165	7486	45.37	Iran
5	North China Electric Power University	161	7137	44.33	China
6	Tianjin University	155	6440	41.55	China
7	Tsinghua University	127	5987	47.14	China
8	Indian Institute of Technology System (IIT System)	123	5718	46.49	India
9	Egyptian Knowledge Bank (EKB)	105	3494	33.28	Egypt
10	Nanyang Technological University	102	7818	76.65	Singapore

Note: The meanings of TP, TC, and ACPP indicators are as described above.

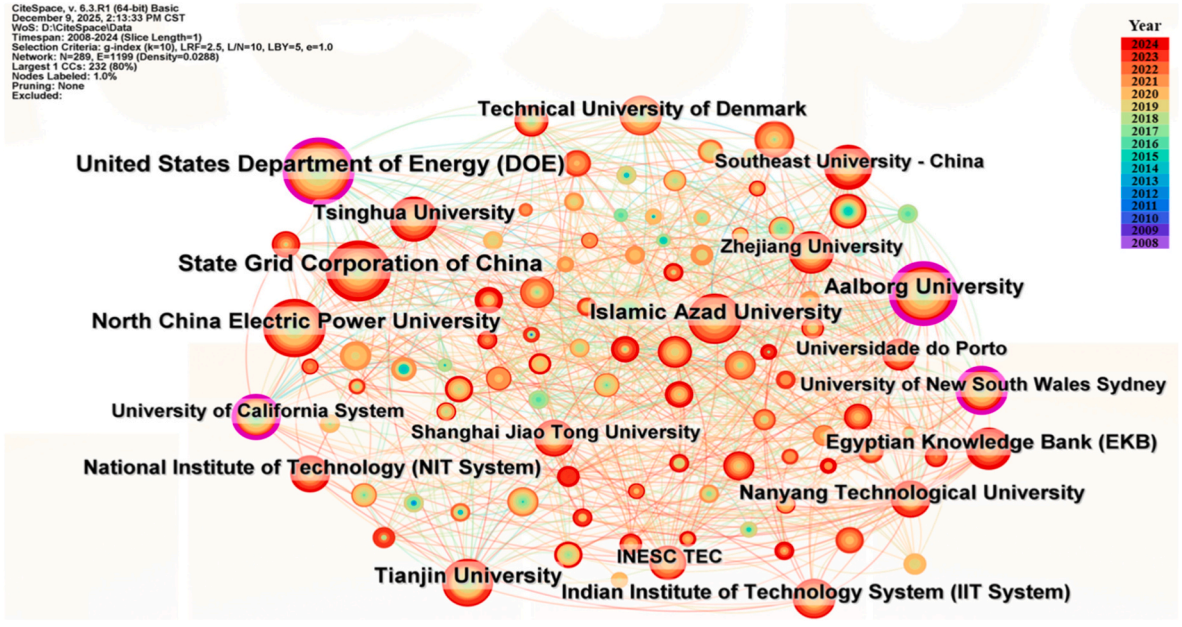


Fig. 4. Institution collaboration network. Note: The node labels in the figure indicate the name of the institution. The size of the font label indicates the number of articles published by the institution. For the convenience of analysis, the threshold range is set: When the frequency of institution collaboration >10, the label is shown in the figure. The linked lines of the nodes in the figure indicate the existence of a cooperative relationship between institutions. The color of the linking line represents the time when the institutions first cooperated. The nodes with purple outer circles indicate their intermediary centrality.

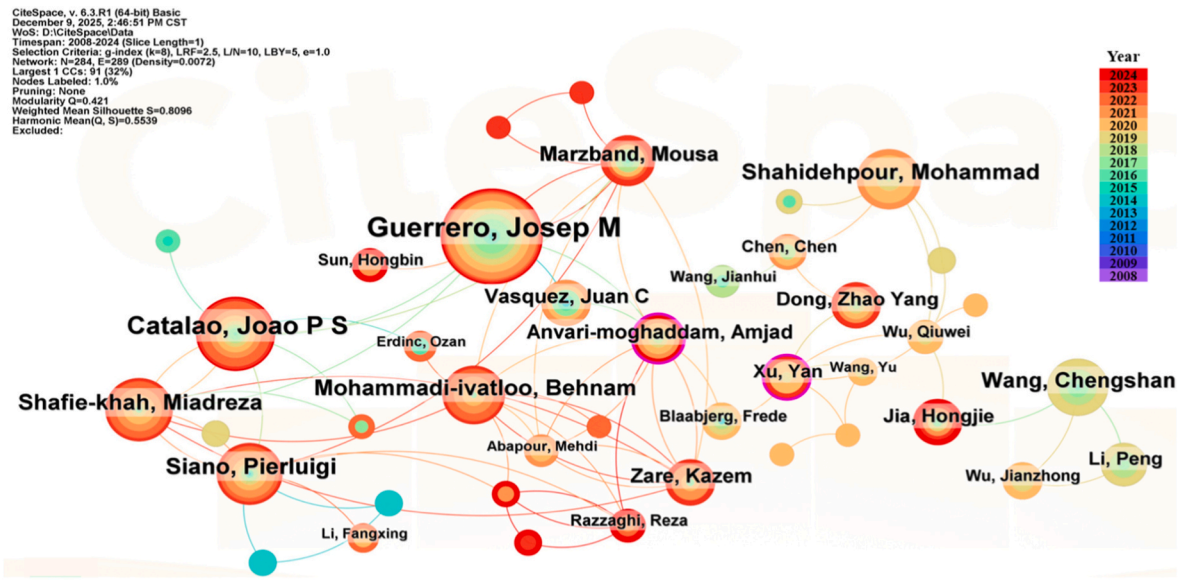


Fig. 5. Author collaboration network. Note: The node labels in the figure indicate the name of author. The size of the font label indicates the number of articles published by the author. For the convenience of analysis, the threshold range is set: When the frequency of author collaboration ≥5, the label is shown in the figure. The linked lines of the nodes in the figure indicate the existence of a cooperative relationship between authors. The color of the linking line represents the time when the authors first cooperated. The nodes with purple outer circles indicate their intermediary centrality.

framework, such fragmentation of the author network does not reflect a decline in collaborative efficiency. Rather, it is a natural manifestation of diverse emerging niches undergoing accelerated experimentation across varying institutional and application contexts, prior to achieving stable "regime integration".

To analyze the primary contributors, we select the top 10 authors based on the number of publications, as shown in Table 5. Among them, Guerrero has made the most significant contribution, as his proposed three-level microgrid control architecture laid the foundation for d decentralization system design [45]. In addition, he has made systematic contributions in key areas such as multi-energy complementary systems, VPPs, and P2P energy trading [36,46]. Other major contributors can be categorized into three levels: In the areas of market and intelligent dispatch, Vale and Faria focus on complex algorithm optimization for VPPs [47–49], while Siano emphasizes the design of blockchain-based P2P transaction architectures [50,51]. In the areas of uncertainty and demand response, Catalão and Shafie-khah focus on addressing renewable energy integration and privacy protection at the smart home and distribution grid levels [40,52,53], while Zare emphasizes strategies for hydrogen storage to counter market fluctuations [54,55]. In physical control and multi-energy systems, Wang establishes the pivotal role of flexible breakpoints in coordinated voltage and reactive power control for active distribution grids [41,56]. Shahidehpour emphasizes resilience enhancement in interconnected microgrids [57,58], while Jia explores the "virtual energy storage" value of thermo-electric coupling systems [59,60].

Table 5
Top 10 authors by publication output.

Author	TP	TC	ACPP	H-Index
Guerrero, Josep M.	96	9547	99.45	56
Vale, Zita	64	3305	52.46	35
Catalão, João P. S.	63	2624	43.02	29
Siano, Pierluigi	48	3411	71.06	28
Wang, Chengshan	47	2721	57.89	32
Shahidehpour, Mohammad	47	3029	64.45	29
Shafie-khah, Miadreza	42	1805	42.98	24
Jia, Hongjie	33	1537	46.58	22
Zare, Kazem	32	1803	56.34	21
Faria, Pedro	32	1277	39.91	18

Note: H-index refers to the number of papers by a researcher or group that have been cited at least H times. The meanings of TP, TC, and ACPP indicators are as described above.

4. Research hotspots analysis

4.1. Keyword analysis

We employ keyword co-occurrence and cluster analysis to reveal cutting-edge trends in the research field. The analysis of highly cited articles (see Appendix A) and co-cited articles (see Appendix B) present in the appendices further supplements the systematic identification of seminal literature within the research domain.

High-frequency and highly central keywords often reflect research hotspots and development trends within a field. Based on keyword frequency (see Fig. 6 and Table 6), "demand response" ranks first with the highest frequency, followed closely by "optimization", "management", "energy storage", and "energy management". This indicates that research focus has expanded beyond mere distributed energy integration issues to encompass customer-side response, system operation management, and optimization scheduling [61,62]. From a network structure perspective, "distributed generation", "distributed power generation", "voltage control", and "management" exhibit significant centrality, frequently appearing in scenarios such as microgrids, VPPs, and distributed control systems [63–65]. Overall, this network configuration reflects the technical-economic essence of energy decentralization: as the penetration rate of distributed energy increases, the marginal balancing costs of power systems rise sharply. Relying solely on traditional approaches like grid expansion and reserve capacity has become economically unsustainable. This trajectory highlights a fundamental shift in the field's primary challenge: moving from the physical bottleneck of "how to integrate more energy sources" to the governance dilemma of "how to coordinate a massive number of actors". Consequently, both academia and industry are now exploring ways to harness the flexibility potential on the consumer side to address the random fluctuations caused by energy technologies and real-world demands.

Based on keyword co-occurrence analysis, we employ the Log-Likelihood Ratio (LLR) algorithm for keyword clustering, generating a

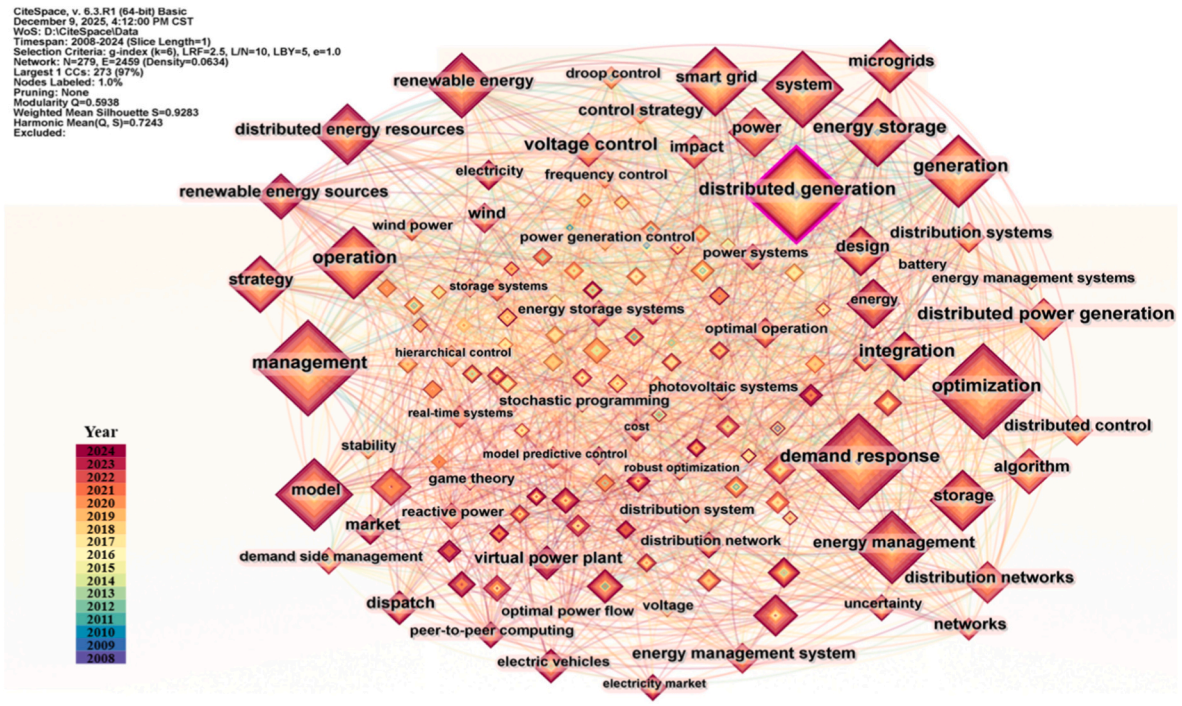


Fig. 6. Keyword co-occurrence network. Note: The node labels in the figure indicate the keywords in the literature. The size of the font label indicates the frequency of keyword occurrences. For the convenience of analysis, the threshold range is set: When the frequency of keyword ≥30, the label is shown in the figure. The line of nodes represents the occurrence of two keywords in one article. The color of the linking line represents the time when the keywords co-occurrence. The nodes with purple outer circles indicate their intermediary centrality.

Table 6
High-frequency keywords in energy decentralization research (2008–2024).

Rank	Count	Centrality	Keywords	Year
1	1007	0.06	demand response	2008
2	891	0.12	distributed generation	2008
3	883	0.06	optimization	2012
4	876	0.07	management	2010
5	677	0.03	system	2011
6	666	0.07	generation	2010
7	627	0.05	energy storage	2010
8	598	0.05	smart grid	2010
9	594	0.02	model	2012
10	587	0.04	energy management	2010
11	574	0.05	operation	2012
12	569	0.05	renewable energy	2011
13	553	0.05	distributed energy resources	2008
14	454	0.03	storage	2012
15	452	0.05	power	2010
16	404	0.03	strategy	2013
17	390	0.03	design	2009
18	367	0.03	microgrids	2012
19	353	0.04	algorithm	2012
20	327	0.01	energy	2008
21	310	0.05	integration	2011
22	280	0.04	renewable energy sources	2015
23	280	0.04	distribution networks	2013
24	264	0.07	voltage control	2012
25	254	0.09	distributed power generation	2013
26	231	0.00	electric vehicles	2013
27	224	0.03	wind	2013
28	217	0.03	virtual power plant	2008
29	202	0.02	framework	2016
30	200	0.02	demand side management	2012

Note: Count is the total number of times a keyword appears across all analyzed literature; Centrality measures a keyword's ability to serve as a "bridge" within the network, with high centrality indicating it functions as a core hub across disciplines; Year denotes the year a keyword first appeared in the dataset.

keyword cluster analysis map (Fig. 7). This further categorizes and summarizes similar hotspots, highlighting core research directions: (1) Distributed energy system (Cluster #2, #3): As the physical foundation of this field, it encompasses engineering practices such as microgrid structural design, renewable energy integration, and energy storage configuration, reflecting a relatively mature technological pathway [66]. (2) Emerging technology applications (Cluster #0): Exploring P2P energy trading and transactional energy mechanisms centered on emerging digital technologies such as blockchain [67,68]. (3) Smart grid and demand-side flexibility (Cluster #0, #1, #4, #5). Centered on demand response, this approach leverages information and communication technology (ICT) and dynamic pricing mechanisms to enhance load flexibility, providing a management framework for supply-demand interaction and community-level coordination within distributed systems [69,70]. (4) Power systems and markets (Cluster #0, #1). Addressing uncertainties arising from high penetration of renewable energy, the study focuses on adaptive adjustments to VPPs, distribution planning, and market mechanisms [69,71,72]. (5) Energy management and optimization (Cluster #1, #3, #4): The study commits to developing methodologies such as distributed optimization and game-theoretic modeling, aiming at achieving precise scheduling, economic operation, and enhanced energy efficiency in complex energy systems [70,73]. (6) Energy governance and institutional arrangements (Cluster #0, #1, #3, #4, #5): The study focuses on the reconstruction of governance structures, institutional rules, and multi-stakeholder interaction mechanisms in the context of energy decentralization [74]. Collectively, these clusters form a multidimensional knowledge map that integrates physical, informational, and institutional layers, revealing energy decentralization as an intrinsic property of complex adaptive systems. The intrinsic mechanism behind hotspot formation lies in the fact that isolated technological breakthroughs can no longer independently sustain system operations. Instead, they must rely on flexible market pricing and inclusive governance frameworks to provide environmental support. This cross-level complementary structure is precisely the key to breaking down disciplinary barriers and achieving overall optimization of energy system efficiency.

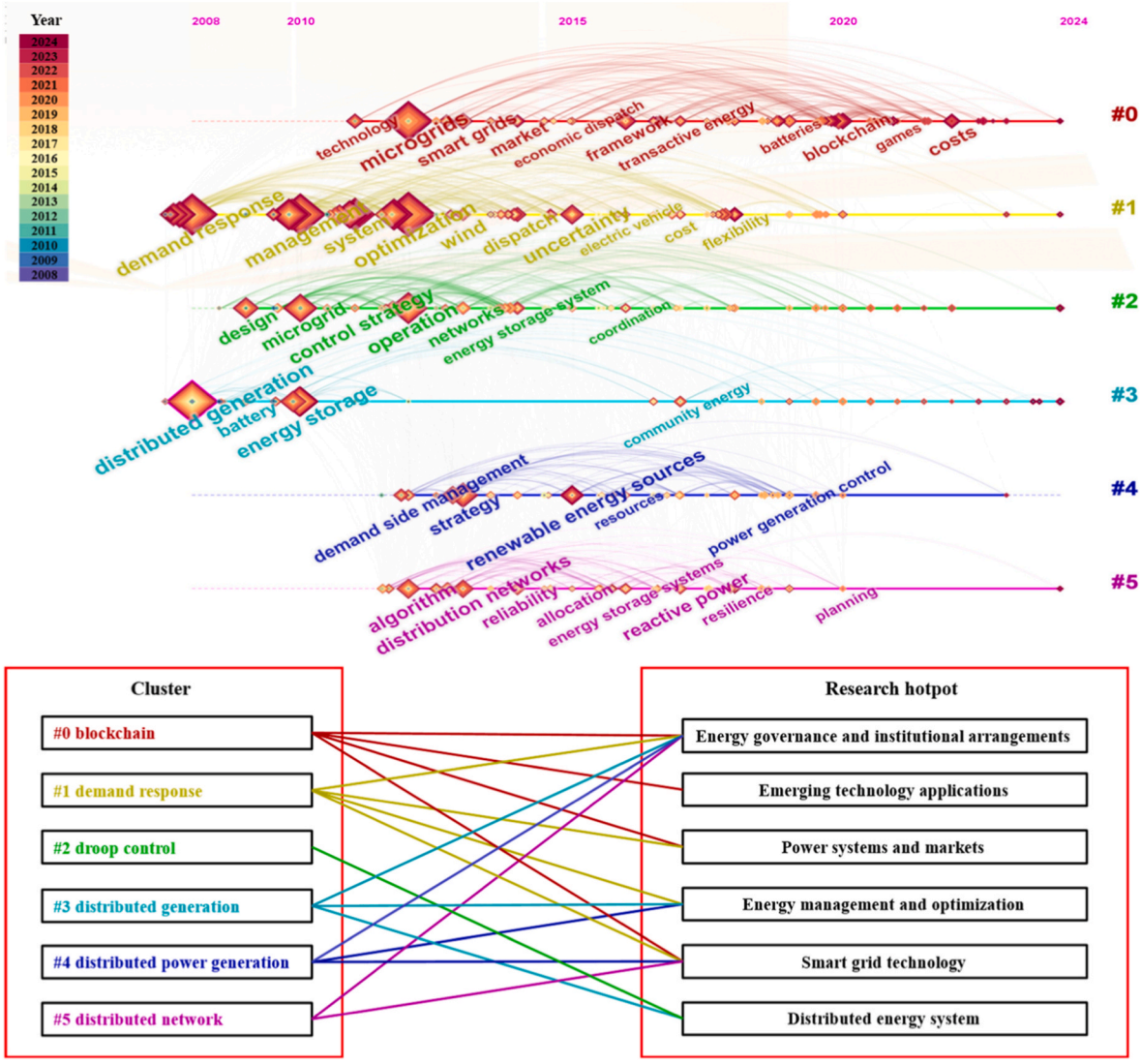


Fig. 7. Keyword timeline mapping. Note: Each line of node labels in the figure is the main keyword in the right-hand clustering. The size of the nodes indicates the frequency of key occurrences, and a larger node indicates a higher cumulative frequency of keyword occurrences. The line between nodes indicates that two keywords appear in the same literature.

4.2. Burst keyword analysis

In order to grasp the dynamic change of research hotspots, we carry out burst keyword analysis (see Fig. 8) and interprets the phased shifts in research themes through the MLP. Phase I: Exploration phase focused on establishing a technical niche and system feasibility ("smart grid" "microgrid" and "stability" appeared frequently). Research focused on validating the operability of distributed energy within existing power system framework [75]. Phase II: Transition to a collaborative integration phase centered on institutional adaptation ("power generation control" "optimization" and "load modeling" appeared frequently). During this stage, the limitations of the existing power regime in addressing fluctuating resources gradually became apparent. Practical pressures stemming from operational efficiency and system costs drove research to focus on how institutional rules could be adjusted to accommodate and coordinate emerging technological niches [76]. Phase III: Further evolution into a system restructuring phase centered on governance reconstruction ("blockchain" "peer-to-peer computing" and "real-time systems" appeared frequently). As the scale of prosumers and the complexity of interactions significantly increased, traditional centralized coordination models revealed structural bottlenecks in information processing, transaction costs, and responsibility allocation. Research began shifting toward multi-agent collaboration, disintermediation, and automated governance solutions [77].

Overall, research on energy decentralization follows a progressive evolutionary path, advancing from "technological embedding" to "institutional coordination", and ultimately to "governance reconfiguration". The lagged emergence of institutional themes relative to technical ones does not stem from a lack of scholarly attention. Rather, it likely reflects the sequential logic of the real-world energy transition. Specifically, in the early stages, technologies such as distributed generation, microgrids, and energy storage are typically embedded as niches within the incumbent centralized system. Primary challenges lie in engineering aspects like equipment integration, system stability, and operational optimization; consequently, research prioritizes technical feasibility and system performance. As distributed resources expand in scale and operational complexity, technical niches begin to exert spillover effects on existing market rules, dispatch mechanisms, and regulatory frameworks. Constraints within the incumbent regime—regarding price formation, liability allocation, and incentive compatibility—become increasingly pronounced. At this stage, relying solely on engineering optimization is insufficient to address the systemic



Fig. 8. TOP 15 keywords with the strongest citation bursts. Note: The red line indicates periods when the keyword suddenly emerged, while the blue line represents other periods without sudden emergence. Year, Begin, and End denote the year of the keyword's first appearance, the year of its outbreak, and the year of its conclusion, respectively. Strength refers to the numerical value of research intensity.

pressures caused by volatility, heterogeneity, and high-frequency interactions. Accordingly, the research focus extends to institutional coordination and market design. Furthermore, as widespread prosumer participation, P2P trading, and multi-actor coordination become the norm, the limitations of traditional centralized coordination—particularly regarding information processing and governance costs—are magnified. This drives a scholarly shift from institutional alignment to broader governance reconfiguration and the design of multi-actor coordination mechanisms.

5. Research trends analysis

Drawing on the analysis of burst keywords, evolutionary paths, and collaboration networks, we argue that the future trajectory of energy decentralization will not merely follow a linear path of technological deepening. Instead, it is gradually exposing a series of strategic institutional and governance tensions. These tensions not only determine the evolution of research agendas but also directly dictate the real-world feasibility and scalability of decentralized models.

①The tension between technology diffusion and institutional alignment: The "regulatability" of P2P and VPPs. Bibliometric results indicate a significant burst in technical keywords such as blockchain, P2P energy trading, and VPPs in recent years. However, research on corresponding market rules and regulatory frameworks has lagged behind. This asymmetry reflects a core strategic dilemma in reality: while decentralized trading mechanisms enhance flexibility, they are challenging existing systems of metering, settlement, and liability allocation. Future research urgently needs to focus on regulatory sandboxes, layered market designs, and data governance mechanisms. It is crucial to systematically assess whether P2P markets and VPPs can achieve scale under various grid constraints without significantly increasing systemic risk.

②The trade-off between community energy expansion and distributive justice. Topics such as community energy and prosumer participation have gained rapid momentum recently, yet related studies show marked heterogeneity across regional and institutional contexts. This suggests that energy decentralization does not automatically translate into energy equity; its actual distributional effects are highly dependent on property rights structures, entry barriers, and policy designs. A critical strategic question is whether community energy mitigates energy inequality or merely creates new rent-seeking opportunities for high-income groups. Therefore, future research must adopt a lens of distributive justice and institutional design to empirically examine the long-term impact of different decentralized models on social inclusiveness.

③The conflict between enhancing system resilience and managing complexity. Although decentralized systems are often viewed as a key pathway to improving energy resilience—evidenced by the expansion of keywords and author networks toward climate shocks, extreme events, and uncertainty management—existing literature remains largely focused on technical reliability. Research on the governance of system failure modes under multi-agent coordination remains insufficient. This highlights an underestimated strategic risk: an increase in the number of distributed units may enhance local resilience while simultaneously amplifying overall coordination costs and system complexity. Future research should systematically evaluate the stability boundaries of decentralized architectures and their associated governance costs under diverse climate and load scenarios.

6. Conclusions and prospects

6.1. Conclusion

We conduct literature screening based on the WoS core collection and uses bibliometric tools (CiteSpace) to systematically analyze the

research results in energy decentralization research. We identify and comb the representative countries and regions, research institutions and high-producing authors in this field from 2008 to 2024, and reveal the characteristics and structure of the cooperation network among the main research subjects. Further, we construct a panorama of research hotspots in the field through keyword co-occurrence, clustering visualization, and burst analysis. This clarifies the current dominant topics and technology paths, and identify the research frontiers that are developing rapidly. The findings are as follows.

(1) The overall publication volume in the field of energy decentralization exhibits a noticeable upward trend. China, USA, and Demark stand out for their contributions to the field of decentralized energy. The research achievements of State Grid Corporation of China, DOE, and Aalborg University are significant, and Professor Guerrero has a strong academic influence in this field. Regarding cooperation analysis, there are relatively close cooperation links between countries and institutions, and authors have formed various independent cooperation network structures.
(2) Research hotspots exhibit thematic diversity. “Demand response” has the highest frequency, while “distributed generation” has the highest centrality value, making them focal points in the research field. The hot topics mainly include distributed energy systems, emerging technology applications, smart grid and demand-side flexibility, power systems and markets, energy management and optimization, and energy governance and institutional arrangements.
(3) Future research on energy decentralization will revolve around the following core topics: First, it must address the coordination between technology diffusion and institutional alignment, with a specific focus on the regulatability and scalability of emerging organizational forms—such as P2P trading and VPPs—within incumbent electricity markets and regulatory frameworks.; second, scholars should systematically assess the distributional effects of community energy and prosumer participation. This involves examining the long-term impacts on social equity and inclusiveness through the lenses of property rights structures, entry barriers, and institutional design; third, research needs to explore the resilience boundaries of decentralized architectures under climate shocks and extreme scenarios, highlighting the governance costs and stability constraints imposed by the rising complexity of multi-agent coordination.

6.2. Results discussion

The identified research hotspots such as key smart grid technologies, emerging technologies application, and management optimization for DERs are highly consistent with technology evolution and research priorities highlighted in existing reviews [14,15]. This result further validates the continued technological dominance of the field over the past decade or so from a bibliometric perspective. However, unlike most reviews that focus on a single direction, our analysis of high-frequency keyword co-occurrence and bursts reveals a rapid rise in topics like “energy resilience”, “community governance”, “intelligent control”. This shift indicates that decentralization research is evolving from “technology-driven-market-driven” to “technology-enabled-market”.

Our research reveals that energy decentralization is evolving through a profound triadic coupling of technology, market, and society. The keywords we identified—such as “voltage control” and “demand side management”—alongside emerging technology applications and distributed energy systems, not only corroborate existing reviews' assessment of a “technology accumulation phase” [78,79], but also reveal an economic transformation in technological attributes. As demonstrated in the studies by Wang et al. (2021), Li et al. (2023), and Huang et al. (2023), cutting-edge technologies such as consensus algorithms and adversarial networks not only resolve underlying physical scheduling challenges but also fundamentally provide trust mechanisms for privacy protection and risk hedging in decentralized trading [80–82]. This signifies that technology has ascended to a higher dimension as the digital infrastructure underpinning market mechanisms and unlocking resource potential. As issues like “community governance” and “energy resilience” come to the fore, this “technology-market” complex is being deeply embedded within broader social structures. Research paradigms are shifting from pure “technological-economic rationality” toward “socio-technical systems” [83]. In summary, existing literature and the quantitative analysis presented herein collectively point to a conclusion: energy decentralization is no longer an isolated technological iteration, but rather a synergistic process where “technology empowers markets, markets guide behavior, and society reshapes rules”.

The evolution of research hotspots not only reveals shifts in the knowledge structure within the field of energy decentralization but also reflects the challenges and structural contradictions in aligning it with real-world energy policy and governance practices. First, regarding energy system stability, there exists a misalignment between accelerated technological iteration and lagging market mechanisms. We observe that the focus of knowledge production has shifted from physical access to flexibility management and market reshaping. However, while current policies—such as the EU's REPowerEU and U.S. Smart Grid Investment Program—vigorously promote infrastructure digitization, corresponding market trading mechanisms and ancillary service systems remain ill-equipped to accommodate the complex dispatch requirements of high-penetration distributed resources. Second, in terms of energy equity and accessibility, the escalating complexity of systems heightens the risk of exclusivity in reaping innovation dividends. As research advances toward intelligent integration, both technological and capital barriers have significantly risen. Despite global climate policies (such as China's “dual carbon” goals) advocating for inclusive transformation, technology pathways heavily reliant on algorithms and automation may trigger a new digital divide. This could exclude marginalized groups lacking technological capabilities from benefiting from decentralized systems. Third, the uneven diffusion of regional policies and institutional development also constrains the global deployment of decentralization technologies. Although China, USA, and Denmark—which dominate the research field—have developed relatively mature policy portfolios for electricity market integration, flexibility pricing, and institutional pilot programs, their experiences heavily rely on existing market foundations and governance capabilities. This makes them difficult to apply in emerging economies still in the early stages of institutional development. Such asymmetries in policy diffusion constrain the release of distributed systems' potential efficiency and hinder the universal deployment of global energy transitions.

Notably, the rapid advancement of artificial intelligence presents new policy opportunities for energy system governance: The EU's Artificial Intelligence Act, China's “New Energy System” strategy, and the U.S. DOE's Digital Grid Initiative all designate AI as a critical enabler for the transformation of energy governance. The application of AI in load forecasting, dispatch optimization, and risk management not only enhances system efficiency but also provides policymakers with new tools for designing dynamic, data-driven market mechanisms [84]. Overall, the future development of energy decentralization requires further strengthening the synergistic perspective of “technology-institution-society” dimensions to promote the deep integration of research outcomes with policy implementation. On the one hand, an inclusive innovation support and governance framework should be established at the policy level to ensure the fairness and security of the energy digital transformation; on the other hand, the academic community must continue to deepen interdisciplinary research to provide more explanatory and forward-looking theoretical support for global energy policy, thereby facilitating the effective implementation of energy decentralization at both the strategic and practical levels.

6.3. Shortcomings and prospects

Although we strive to be comprehensive in terms of methodology and coverage, it still inevitably has certain limitations: (1) Regarding data sources, considering the authority of databases in the field of research, we are mainly based on the English-language literature of the WoS core database. However, due to WoS's limited coverage of non-English journals, regional publications, and grey literature, this may to some extent lead to biases in understanding research dynamics in non-English-speaking countries. For instance, in regions such as Africa and South America where energy decentralization systems are rapidly developing, relevant research often relies primarily on local languages or regional publications as its main medium. Consequently, such studies may not be fully reflected in this analysis, thereby somewhat undermining the comprehensive presentation of the global research landscape. (2) The bibliometric approach employed in this study emphasizes the quantitative representation of literature volume, citation relationships, and knowledge structures, thereby revealing the macro-level patterns of academic networks and research evolution. However, bibliometric analysis primarily focuses on external structural characteristics and has limited capacity to reveal theoretical evolution pathways, causal mechanisms, and methodological differences within research content. (3) Regarding sample construction, we employed a keyword-based retrieval strategy to ensure systematic coverage of relevant research. However, in fields characterized by high conceptual overlap, this approach remains sensitive to boundary definitions. Specifically, the term "energy decentralization" exhibits semantic overlap with related topics such as distributed energy systems, microgrids, and prosumer participation. While we have rigorously controlled the sample scope through explicit conceptual definitions and manual screening, it remains possible that a small number of adjacent studies—whose primary focus may not be the structural shift toward decentralization—have been included.

Future research may proceed along the following directions: First, we must overcome the limitations of single-database reliance by constructing a composite data pool encompassing Scopus, CNKI, Dimensions, and multilingual literature. Emphasis should be placed on mining grey literature, such as government reports and industry white papers. Through multilingual retrieval and cross-database comparative analysis, we can correct the selective biases inherent in single-source data, thereby more accurately reconstructing the full landscape of energy decentralization policies and practices across global regions. Second, in terms of methodology, it is recommended to combine bibliometric analysis with qualitative approaches such as Delphi surveys, expert interviews, or policy content analysis. Building upon the identification of macro trends, this approach enables an in-depth examination of the theoretical logic, interest dynamics, and social driving mechanisms underlying the data, thereby achieving complementarity between structural characteristics and content depth. Third, future research could further strengthen interdisciplinary and cross-regional comparative analysis, particularly by examining the divergent pathways of energy decentralization development under different policy frameworks and market mechanisms, and their implications for global energy governance, equitable transition, and digitalization strategies. Finally, as technologies such as artificial intelligence, big data, and blockchain become deeply integrated into energy systems, future research should also examine how these technologies reshape energy governance models and policy evaluation frameworks. It should explore their potential applications in supporting the dual carbon goals, optimizing distributed markets, and advancing community energy governance.

Credit author statement

Fengfu Mao: Conceptualization, Resources, Writing - Reviewing, and Funding acquisition. Jing Lin: Software, Data curation, Formal analysis, and Writing - original draft. Yuqiao Hou: Investigation, Revision, Visualization, Review & Editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2026.102097.

Data availability

No data was used for the research described in the article.

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