

Research on power systems under extreme weather: A bibliometric and BERTopic modeling analysis

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ABSTRACT

The increasing frequency and severity of extreme weather events, driven by global climate change, makes ensuring the resilience of power systems a pressing challenge. To comprehensively analyze the operation of power systems under extreme weather conditions, this study employs bibliometric and BERTopic modeling methods. Based on 2,076 research articles retrieved from the Web of Science database between 2001 and 2025, we analyzed publication trends, identified leading countries and institutions, and revealed core research topics. Our results indicate that the number of publications has shown an accelerated growth phase since 2016. The USA and China are the dominant research forces, with the highest number of publications and citations, and the highest publication impact. Furthermore, topic modeling identified 11 core research clusters, among which “resilience framework and restoration strategies”, “climate risks in the context of energy transition”, and “hydropower and climate risks” form the foundational pillars of current research. Finally, this study proposes an integrated framework, points out future research directions, including multi-technology synergy, data-driven methods, and more. This research systematically maps the directions within the field and provides a reference for guiding future in-depth studies aimed at enhancing the resilience of power systems to extreme weather.

KEYWORDS

Power system resilience, climate risk, energy transition, energy policy, bibliometric analysis.

1 Introduction

Under the background of increasingly intensified global climate change, the frequency, intensity and complexity of extreme weather events, such as heat waves, cold waves, rainstorm, hurricanes, are growing in an unprecedented manner, posing a serious challenge to human society^[1]. As a critical infrastructure, the power system is fundamental to modern society, which is profoundly dependent on a reliable electricity supply. Consequently, power outages can severely disrupt livelihoods^[2]. Moreover, over 50% of the 138 worldwide power outages have been found to be caused by unusual weather^[3]. For instance, during the 2021 cold wave in Texas, widespread and prolonged power outages occurred due to a surge in heating demand, a sharp decline in power generation, and a shortage of external support capacity^[4]. In 2012, Hurricane Sandy crippled the power grids across multiple coastal states in the United States, triggering extensive blackouts that affected over 8.5 million customers^[5]. In 2022, during an extreme heatwave and drought in Sichuan, China, overlapping with a peak electricity consumption period, hydropower generation was severely constrained. Despite the region's abundant hydropower resources, the daily electricity supply gap reached up to 370 million kWh. Concurrently, residential electricity demand surged sharply, with the peak load and daily electricity consumption increasing by 14% and 93.3% respectively, which further intensified the imbalance between supply and demand^[6,7]. These events have not only exposed the vulnerability of power systems at the physical level but have also highlighted management deficiencies in areas such as energy policy planning, long-term climate risk assessment, and cross-

sectoral emergency coordination. Therefore, the complex correlation between extreme weather and power systems stability has become a global focus of attention.

The impact of extreme weather on power systems is multifaceted. At the physical level, strong winds, ice accumulation, and floods can directly damage transmission towers, wash away their foundations, leading to line short circuits and equipment failures^[8,9]. At the operational level, during heatwaves, the surge in cooling loads (such as from air conditioning) and during cold spells, the sharp rise in heating demand can trigger a sudden spike in electricity consumption, far exceeding the grid's designed capacity^[10]. Meanwhile, droughts can lead to a sharp decline in hydropower output, while storms may compel large-scale wind and photovoltaic farms to disconnect from the grid, resulting in a significant generation shortfall^[11]. This dual imbalance between supply and demand can easily trigger cascading failures, which may ultimately culminate in large-scale, prolonged power outages. First, the lag in energy policy may exacerbate the crisis. Policies often lack the dynamic responsiveness to fluctuations in renewable energy output, extreme weather events, and changes in market signals. This rigidity thereby aggravates market failures and energy shortages^[12]. Secondly, risk governance systems often fail to incorporate the long-term trends of climate change into power system planning and investment. They also neglect the probability and impact depth of extreme events. This oversight makes it difficult for the system to transition from passive disaster relief to proactive resilience-based risk governance^[13]. Finally, power restoration involves not only the energy sector but also requires close coordination among sectors such as transportation and communications, where unclear allocation of responsibilities,

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information barriers, and imperfect emergency response coordination mechanisms can significantly prolong power outage recovery time and amplify socio-economic losses^[14,15]. Therefore, delving into the intricate relationship between extreme weather and power systems, and systematically reviewing the current state, hot topics, and cutting-edge developments in this field, has become an urgent issue of shared concern for both academia and industry.

In recent years, the volume of research literature on extreme weather and power systems in authoritative databases such as Web of Science has seen a marked increase. Research perspectives encompass diverse dimensions including system planning, meteorological prediction, operational control, and restoration strategies, all aimed at enhancing the resilience of power systems to extreme weather. However, the highly fragmented and interdisciplinary nature of this field makes it challenging for traditional literature review methods to fully capture its overall knowledge structure and research context. While existing reviews offer valuable insights, they are often confined to specific subsystems (e.g., distribution networks^[15], hydropower^[16], or district energy^[17]) or traditional component-level frameworks^[10], lacking a holistic perspective on cross-system coordination and paradigm shifts. Therefore, it is imperative to adopt a data-driven bibliometric approach to systematically uncover the overall thematic landscape and evolutionary trajectories of this field.

Therefore, this study adopts an integrated approach combining bibliometrics and topic modeling to conduct a systematic review and analysis of the literature in the field. The main contributions are summarized as follows: (1) This article presents findings from a bibliometric and topic analysis of power systems under extreme weather, delineating key developmental phases, identifying the most influential countries and institutions, and highlighting the most-cited literature, thereby enabling scholars to better grasp the research landscape and evolutionary trajectory of this field. (2) Eleven major research hotspots are identified, offering clear directions for future studies and encouraging valuable, impactful research. This work helps researchers understand the current state, emerging frontiers, and future priorities in power system resilience to extreme weather, providing guidance and reference for deeper investigation.

The paper is organized as follows: Section 2 presents the research framework and methodology; Section 3 presents our findings regarding research on extreme weather events in power system, covering publications, countries, institutes, the most-cited papers, research hotspots, and the evolution of studies in this field; finally, conclusion is provided in Section 4.

2 Research framework and methodology

2.1 Research framework

Based on the research objectives of this paper, a framework combining bibliometric analysis with the BERTopic model for research on power systems under extreme weather is shown in Figure 1.

2.2 Data collection and cleaning

The data for this study were sourced from the Web of Science (WoS) core collection database. The selection of WoS was based on its reputation as an authoritative and multidisciplinary database, renowned for its comprehensive coverage of high-quality, high-impact research literature. Its powerful citation analysis tools and widespread use in prior bibliometric research provide a solid foundation for identifying international research trends and ensuring the reproducibility of the retrieval process^[18]. A detailed description of the search strategy is presented in Table 1.

A total of 4,335 records were initially retrieved. Due to the presence of numerous irrelevant articles, a further screening of the search results was performed, ultimately yielding 2,076 publications relevant to the research topic for subsequent analysis. Subsequently, the dataset underwent a standardized cleaning process.

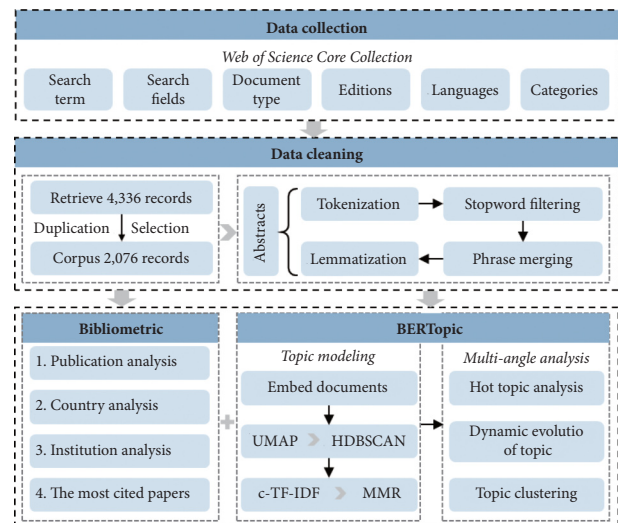


Fig. 1 Research framework.

Table 1 Search details through the web of science database.

Attributes	Set criteria
Editions	Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index-Science (CPCI-S), and Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH)
Web of Science Categories	Energy Fuels, Engineering Electrical Electronic, Environmental Sciences, Economics, among others.
Languages	English
Search term	("extreme weather" OR "extreme climate event" OR "severe weather" OR "weather event" OR "extreme temperature" OR typhoon OR hurricane OR heatwave OR flood OR drought) AND ("power system" OR "electric power system" OR "electric system" OR "power grid" OR "electric grid" OR "power network" OR "power generation" OR "power transmission" OR "energy storage" OR "renewable energy")
Document type	Article or Review or Proceedings paper
Search time	September 1, 2025

2.3 Bibliometric analysis

Bibliometrics is a method employing statistical and mathematical techniques to quantitatively analyze academic literature within a specific field. It is capable of understanding large amounts of unstructured data, interpreting and mapping the accumulated scientific knowledge and evolutionary nuances in mature fields^[19]. Bibliometric analysis has been applied to many fields, such as distributed photovoltaic^[20], power system planning^[21], green supply chain management^[22]. In this study, bibliometric analysis is applied to explore the research landscape of extreme weather and power systems, focusing on publication trends, geographic and institutional contributions, as well as citation impact. To visualize the collaborative networks identified in the analysis, VOSviewer software was utilized. This approach provides an intuitive understanding of research partnerships within the domain.

2.4 BERTopic model

To complement the bibliometric analysis and delve into the topic content of the research, we employed BERTopic, an advanced topic modeling technique based on transformer architectures. It leverages pre-trained BERT models to capture the semantic information of documents, transforming textual data into a set of topics through the aggregation and clustering of word vectors. Compared to popular topic modeling techniques such as Latent Dirichlet Allocation (LDA), it demonstrates superior performance in aspects like utilizing pre-trained embeddings and automatically determining the optimal number of topics^[23].

This analysis was performed on the abstracts of the retrieved literature. The initial cleaning of the abstracts involved deduplication and the removal of blank lines before BERTopic modeling was performed. Subsequently, the text was preprocessed through a series of steps: tokenization (splitting text into words), removal of stop words and irrelevant terms, lemmatization (e.g., reducing “systems” to “system”), and phrase detection to combine relevant unigrams into meaningful multi-word units (e.g., merging “power” and “system” into “power system”). During the BERTopic model training, the `nr_topics` parameter is utilized to regulate topic counts. Given the inherent subjectivity of manual specification, this study employs the ‘auto’ mode, wherein topics with a similarity coefficient exceeding 0.9 are automatically merged to determine the optimal number of topics.

3 Results and discussion

3.1 Results from bibliometric analysis

3.1.1 Publication analysis

The annual number of published papers serves as a key indicator for measuring research intensity and development trajectories within a specific field. Figure 2 illustrates the evolutionary trajectory of research on power systems under extreme weather, which is characterized by distinct stages. From 2001 to 2010, annual publications remained below 10, and review articles were virtually non-existent. From 2011 to 2015, the field entered a period of moderate growth, with the total number of publications steadily increasing to 34. The emergence of review articles during this phase signaled that the research was gradually maturing. The period from 2016 to the present has entered a phase of accelerated growth. The year 2018, in particular, witnessed an explosive surge in publications, with journal articles surpassing conference papers

for the first time to become the primary form of output. This shift indicates a significant enhancement in the quality of research. It also reflects that relevant research is genuinely transitioning from early-stage academic exploration into a practical engineering foundation that supports the enhancement of power grid resilience.

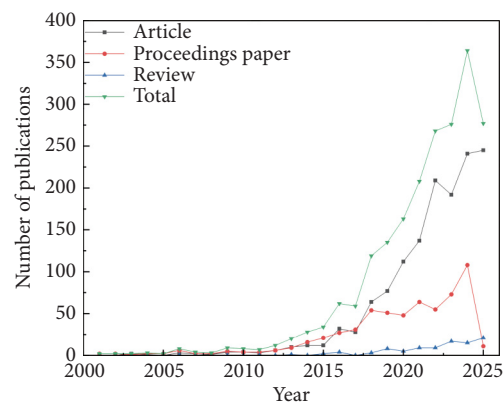


Fig. 2 Number of publications by year.

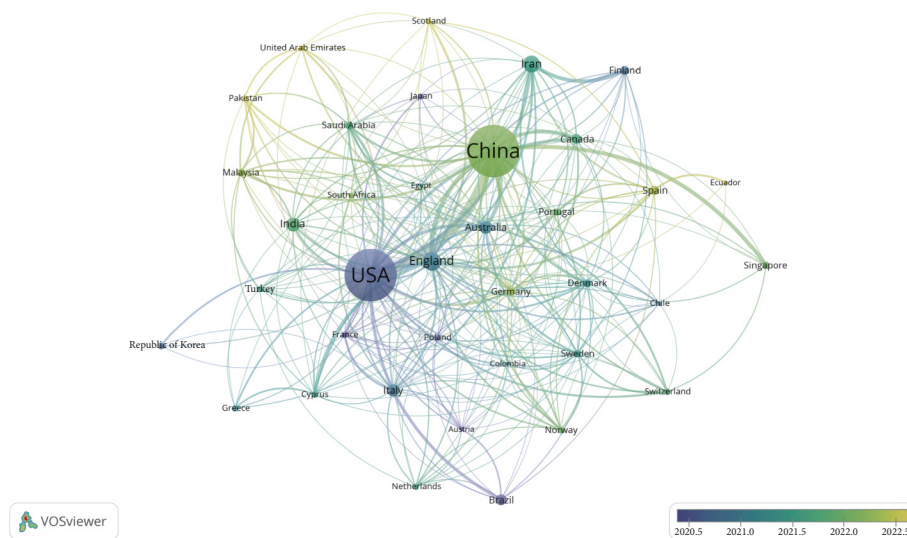
3.1.2 Country analysis

A total of 2,076 articles were published across 88 countries. As shown in Table 2, which lists the top 10 most prolific countries, the United States and China are the two most productive nations, with 727 and 724 publications respectively. Together, they account for 69.89% of the total output. England and Iran have each published over 100 articles. Table 2 also presents citation counts and the H-index (a metric evaluating the quantity and quality of academic output). The United States ranks first with 18,251 citations and an H-index of 65, followed by China with 11,141 citations and an H-index of 50. The United States' leading advantages in total citations and H-index largely stem from its early incorporation of infrastructure resilience into national security strategies. The foundational assessment frameworks and theoretical systems it established possess first-mover advantages. These have been widely adopted by the international academic community. In terms of total citations per publication (TC/TP), Australia (54.44) and England (42.79) rank higher, followed by Iran (30.74) and the USA (25.1). China ranks low in TC/TP with a score of 15.39.

Figure 3 illustrates the collaborative network among 37 countries. Generated using VOSviewer, the network includes only those countries or regions with a minimum of 8 related publications. From a network structure perspective, the USA and China form the absolute core of the network. The USA has established its dominant position through its extensive collaborations with 35 countries, a total link strength of 244, and an influence measured by 18,229 total citations. China, meanwhile, emerges as another key hub through its collaborations with 33 countries, a total link strength of 245, and a literature output of 724 publications. The rapid rise of China as a core node can be attributed to the frequent extreme weather events in recent years. Such events have revealed the defense shortcomings of the power system after accommodating a high share of renewable energy. This has prompted China, in the process of issuing grid anti-disaster upgrading plans, to urgently introduce and align itself with internationally advanced resilience assessment technologies and standard systems. England and Germany serve as core nodes,

Table 2 Top-10 of most productive countries.

Countries	TP	TC	TC/TP	H-index	Cited interval		
					≥500	300–500	100–300
USA	727	18251	25.1	65	2	6	30
China	724	11141	15.39	50	1	3	12
England	129	5520	42.79	33	2	3	8
Iran	106	3258	30.74	30	0	0	7
India	79	678	8.58	13	0	0	1
Australia	72	3920	54.44	24	2	3	1
Italy	69	1331	19.29	17	0	0	3
Brazil	52	985	18.94	15	0	0	1
Canada	47	787	16.74	17	0	0	1
Spain	42	583	13.88	14	0	0	0

**Fig. 3** Countries' cooperation network in extreme weather and power systems research.

establishing partnerships with 32 and 29 nations respectively, acting as bridges connecting the Europe-America and Asia-Pacific clusters. Temporal analysis further reveals distinct chronological patterns. Collaborative ties involving core countries like China and Germany are primarily concentrated around 2022, suggesting a significant recent upsurge in cooperative activity. This recent sharp increase in the density of cross-border collaboration is primarily attributable to the trans-regional extreme weather events in recent years. Such events have exposed the limitations of defense measures undertaken by a single country.

3.1.3 Institution analysis

Since 2000, 200 institutions worldwide have contributed to the literature on extreme weather and power systems. Table 3 lists the ten most prolific institutions among them. The top ten institutions are concentrated in two countries: the USA (5) and China (5). The most prolific institution is the United States Department of Energy, with 166 publications (8.0%), followed by the State Grid Corporation of China at 133 publications (6.4%). In terms of total citations, the United States Department of Energy ranks first with 4,488 citations, followed by the State Grid Corporation of China and the Texas A&M University System. In terms of TC/TP, Texas A&M University College Station ranks first, Texas A&M University System ranks second, and the United States

Department of Energy ranks third. In terms of the H-index, the United States Department of Energy ranks highest with a score of 28, followed by China Southern Power Grid at 17. In summary, the United States Department of Energy emerges as the leading institution in research on extreme weather and power systems.

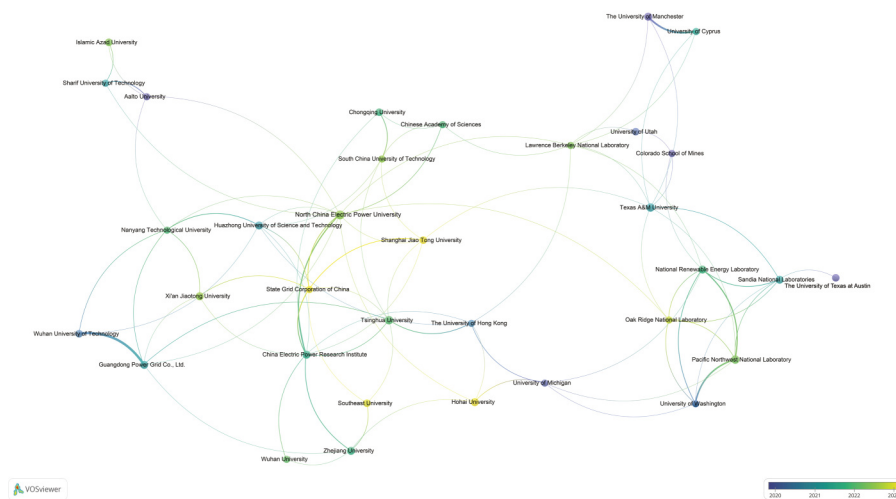
Figure 4 illustrates the collaborative relationships among 34 institutions. This diagram includes institutions with 16 or more related articles. From a network structure perspective, Chinese institutions form the absolute core of the network. Institutions such as North China Electric Power University and China Electric Power Research Institute have established a tight domestic collaboration circle, reflecting China's strengths in industry-academia-research synergy within the power system research field. In contrast, while the United States institutions have smaller node sizes, they have formed distinctive clusters centered around national laboratories. Key players like Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory play pivotal roles in new energy technology research.

3.1.4 The most cited papers

By analyzing the ten most frequently cited papers in the field of power systems research under extreme weather, we can uncover the core knowledge base and research frontiers within this

Table 3 Top-10 of most productive institutions.

Institution	Country	TP	TC	TC/TP	H-index
United States Department of Energy	USA	166	4488	27.04	28
State Grid Corporation of China	China	133	1055	7.93	14
China Southern Power Grid	China	74	793	10.72	17
North China Electric Power University	China	56	851	15.2	15
Pacific Northwest National Laboratory	USA	43	554	12.88	12
Tsinghua University	China	39	1042	26.72	14
Texas A & M University System	USA	38	1049	27.61	14
China Electric Power Research Institute	China	36	215	5.97	7
Texas A & M University College Station	USA	35	1028	29.37	14
University of Texas System	USA	35	617	17.63	11

**Fig. 4** Institutions' cooperation network in extreme weather and power systems research.

domain. As shown in Table 4, these ten highly cited articles are concentrated in a few high impact journals. Among them, “A three-stage resilience analysis framework for urban infrastructure systems”^[24] stands out as the most influential, with a total of 629 citations and an annual average of 48.38. Additionally, “Quantifying the impacts of climate change and extreme climate events on energy systems”^[25] notably holds the highest annual citation rate of 95, accumulating a total of 475 citations. *Structural Safety* and *IEEE Transactions on Power Systems* were the journals that hosted the most cited articles. Meanwhile, the England emerged as the most influential country, contributing five of the most frequently cited papers.

These ten high-impact papers clearly outline the developmental trajectory of research on power system resilience. Early research focused on constructing theoretical evaluation frameworks and quantitative measurement methods, such as framework development^[24,26] and metric studies^[27,28], aimed at establishing theoretical foundations and universal paradigms. Subsequently, research shifted its focus to in-depth analysis of the impact mechanisms linking extreme weather events to climate change and the vulnerabilities within systems. This included examining influence mechanisms^[25,29] and probabilistic assessments^[30,31], with particular emphasis on the interaction between external stressors

and system vulnerabilities. This shift is attributable to the needs of engineering implementation departments. They require a clear understanding of specific fault evolution paths in order to carry out precise equipment reinforcement. In recent years, the research frontier has distinctly shifted toward enhancement strategies and solution design for resilience. This encompasses grid planning based on robust optimization^[32], hardware hardening combined with smart operational strategies^[28], and the construction of resilient architectures utilizing distributed resources like microgrids^[33]. This is mainly because the preliminary theoretical standards have been largely perfected. The current focus of policy assessment has shifted to how to achieve the practical application of disaster prevention and reinforcement solutions at the lowest economic cost.

3.2 Results from BERTopic analysis

3.2.1 Hot topic analysis

The BERTopic model identified 11 distinct research topics, labeled as Topic 0 through Topic 10. Additionally, 963 articles were initially categorized as noise and designated as Topic -1. The embeddings strategy was subsequently employed to reduce outliers, which facilitated the reassignment of articles from the

Table 4 Top-10 of most cited papers.

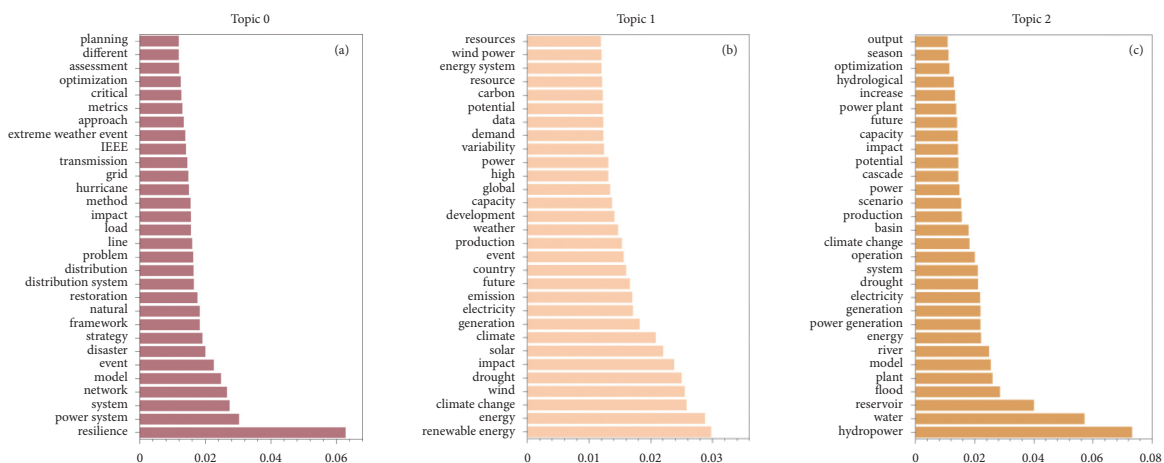
Title	Journal	Country/region	TY	TC	TC/Y
A three-stage resilience analysis framework for urban infrastructure systems ^[24]	<i>Structural Safety</i>	USA China	2012	629	48.38
Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies ^[29]	<i>Electric Power Systems Research</i>	England	2015	534	53.40
Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems ^[27]	<i>IEEE Transactions on Power Systems</i>	England Australia Greece Cyprus	2017	522	65.25
Quantifying the impacts of climate change and extreme climate events on energy systems ^[25]	<i>Nature Energy</i>	Switzerland Sweden Australia	2020	475	95.00
Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures ^[30]	<i>IEEE Transactions on Power Systems</i>	England	2017	447	55.88
Multi-dimensional hurricane resilience assessment of electric power systems ^[26]	<i>Structural Safety</i>	China USA	2014	436	39.64
Robust Optimization-Based Resilient Distribution Network Planning Against Natural Disasters ^[32]	<i>IEEE Transactions on Smart Grid</i>	USA China	2016	417	46.33
Modeling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events ^[31]	<i>IEEE Systems Journal</i>	England	2017	381	47.63
Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement Strategies ^[28]	<i>Proceedings of the IEEE</i>	England Greece Australia	2017	356	44.50
Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience ^[33]	<i>Applied Energy</i>	Republic of Korea	2019	351	58.50

noise category into relevant topics. The 11 relevant research topics are as follows.

3.2.1.1 Topic 0: Resilience framework and restoration strategies

As shown in Figure 5(a), beyond the core search terms, the predominant keywords for Topic 0 include “resilience”, “model”, “strategy”, “framework”, “restoration”, “line”, “load”, “impact”, “method”, “approach”, “metrics”, “optimization”, and “assessment planning”. This field concentrates on developing systematic resilience frameworks and quantitative metrics to assess the impacts of extreme weather events on power systems and to explore effective enhancement strategies^[29,34]. This research direction aims to establish a coherent link between resilience assessment and enhancement measures. At the modeling level, the research focuses on developing optimization models that account for multiple uncertainties. These include, for instance, two-stage robust optimization^[32], mixed-integer programming^[35], and

integrated climate-energy models^[36]. At the technical strategy level, the research delves into specific resilience-enhancement measures. These include integrated strategies for line hardening coordinated with energy storage deployment^[37], robust emergency dispatch strategies^[38], and the development of emergency control schemes based on linear programming optimization models^[39]. At the evaluation level, the effectiveness of the proposed models and strategies is validated through case studies. These studies demonstrate their capability to minimize expected load shedding, optimize investment costs, and significantly enhance the system’s restoration capability^[40]. This research shift from passive response to active planning responds to two main drivers. First, there is policy pressure for grid disaster prevention and mitigation under the frequent occurrence of extreme weather events. Second, power grid enterprises have practical demands to achieve refined asset investment management under limited budgets. These studies have ultimately promoted a comprehensive improvement in the

**Fig. 5** Keyword distribution and scores. (a) Topic 0, (b) Topic 1, (c) Topic 2.

adaptability, rapid recovery capability, and long-term resilience of power systems under extreme weather events^[41,42].

3.2.1.2 Topic 1: Climate risks in the context of energy transition

As illustrated in Figure 5(b), the keyword cluster of Topic 1 encompasses driving factors (climate change, weather), energy composition (renewable energy, wind, solar, resource), system characteristics (variability, capacity), and core challenges (drought, emission, demand). The core of this research direction lies in constructing a comprehensive analytical framework for the climate-energy nexus^[17]. Climate change intensifies the variability and uncertainty of renewable energy output^[43,44], leading to the central challenge of energy droughts in high penetration renewable energy systems^[45]. Through quantitative analysis^[3], reveal that extreme weather events, such as severe cold scenarios, can lead to a 37.6% decline in average photovoltaic power output, severely compromising the electricity supply-demand balance. To address this challenge, the field focuses on exploring multidimensional solutions. At the systemic assessment level, it emphasizes the necessity for a holistic evaluation of all energy resources to construct a more resilient energy system. In terms of resilience enhancement, the focus lies on mitigating the impacts of events like prolonged droughts. Such events severely affect hydropower generation and increase reliance on wind and solar energy. Researchers investigate solutions through optimizing the power supply structure and enhancing system flexibility^[3,46]. At the planning methodology level, efforts are directed toward developing energy planning models that incorporate future climate scenarios. These models integrate the impacts of climate change on wind and solar power generation potential into future capacity planning and global energy strategies. Ultimately, this facilitates the transition of energy systems toward a secure, low-carbon, and climate-resilient future^[45,47]. This research trend indicates a dual necessity for energy management authorities. They must proactively incorporate climate risk considerations into long-term planning while advancing the low-carbon transition. This approach ensures reliable power supply while effectively implementing emission reduction policies.

3.2.1.3 Topic 2: Hydropower and climate risks

As illustrated in Figure 5(c), the keyword cluster for Topic 2 delineates a comprehensive research domain centered on hydropower, addressing the challenges of climate change while

serving the broader energy and power system. Research in this field focuses on enhancing the performance and resilience of hydropower system in complex environments through modelling and optimization techniques. The primary task is to develop multi-temporal and spatial scale optimization models to address scheduling challenges within multi-energy complementary systems integrating hydroelectricity with wind and photovoltaic power. This aims to smooth fluctuations, minimize curtailment of hydro and solar generation, and maximize total electricity output^[48]. The focus on multi-energy complementary scheduling is primarily driven by the policy demand for the flexible regulation capacity of hydropower under the mechanism for ensuring renewable energy integration. Concurrently, significant emphasis is placed on assessing climate change impacts and developing adaptation strategies^[16,49]. This involves a thorough analysis of its spatially heterogeneous effects on river runoff, reservoir storage, and power generation reliability. Furthermore, research explores pathways to enhance the climate resilience of the integrated energy-water nexus by refining operational rules, integrating energy storage technologies, and coordinating multi-objective needs such as flood control and ecological conservation^[50]. Coordinating multiple objectives such as flood control and ecological requirements reflects that hydropower scheduling management needs to strike a practical balance between meeting rigid environmental constraints and ensuring power supply.

3.2.1.4 Topic 3: Microgrid operation control

As illustrated in Figure 6(a), the keywords for Topic 3 encompass system architecture (microgrid, DC, grid, network), operational modes (islanded, operation, mode), control objectives (resilience, stability, frequency), and technical methodologies (control, management, real-time, simulation, model). This field concentrates on the operation and control of microgrids in islanded mode. Research focusing on islanded mode is primarily aimed at meeting the emergency management requirements of ensuring uninterrupted power supply to critical loads under extreme disasters. At the control strategy level, the research focuses on developing real-time management schemes and frequency control algorithms tailored for islanded microgrids. These strategies are typically validated through simulation and case studies to ensure their dynamic response performance supported by energy storage components such as batteries^[51,52]. At the system optimization level, research delves into exploring pathways for resilience enhancement and economic viability in

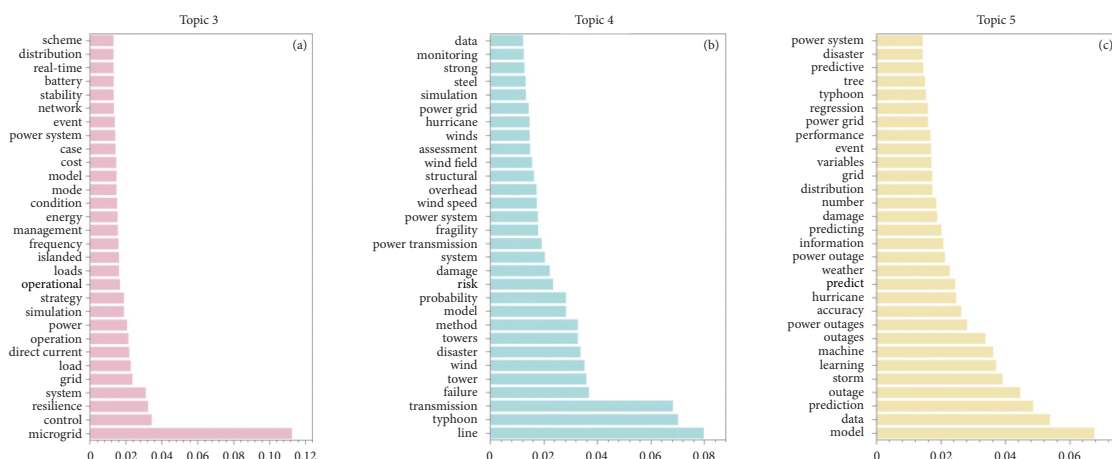


Fig. 6 Keyword distribution and scores. (a) Topic 3, (b) Topic 4, (c) Topic 5.

microgrids. This involves establishing refined models to balance operational costs with power supply reliability, and formulating effective strategies for load shedding or restoration and generation control^[53,54]. Ultimately, these research findings not only enhance the resilience of microgrids themselves but also, through their role as controllable autonomous units within distribution systems, provide crucial technical support and solutions for strengthening the overall resilience of the entire power system in responding to extreme events^[33,55].

3.2.1.5 Topic 4: Transmission line physical vulnerability

As can be seen from Figure 6(b), the keyword clusters for Topic 4 encompass physical facilities (line, transmission, tower, overhead, steel), hazard factors (typhoon, hurricane, wind speed, wind field), failure modes (failure, damage, disaster), and analytical methods (model, probability, fragility, simulation, assessment). The core objective of this research direction is to develop advanced assessment methodologies and probabilistic models, utilizing tools such as simulation and monitoring data, to accurately evaluate the damage risk to power transmission infrastructure caused by extreme weather events^[56]. The refined quantification of physical facility vulnerability is primarily aimed at meeting the management demands of differentiated investment and precise reinforcement for grid disaster prevention. The focus shifts from the failure of individual components to encompassing the cascading consequences across the entire power system^[57,58]. Research recognizes that the physical failure of local components may evolve into system-level widespread blackouts through cascading effects, ultimately resulting in substantial economic and societal ramifications^[59,60]. Consequently, this field is dedicated to constructing a complete analytical chain. This chain links meteorological hazards to component failure and further extends to systemic risk. By doing so, it provides a theoretical foundation and technical support for enhancing grid resilience under extreme weather.

3.2.1.6 Topic 5: Power outage prediction

As shown in Figure 6(c), Topic 5 centers on the formulation of high-fidelity prediction models designed to mitigate power outage risks precipitated by extreme weather events, such as hurricanes and severe storms. This approach leverages advanced computational modeling and multi-source data fusion to enable high-fidelity, dynamic forecasting of power grid risks induced by extreme weather events^[61,62]. The core lies in constructing an

intelligent analysis chain that transforms data into predictions ultimately serving decision-making. Research has generally focused on integrating coarse weather forecast data with power grid physical information and even socioeconomic variables through machine learning techniques (such as regression and ensemble learning) and deep learning technologies (such as CNNs and LSTMs)^[63]. The objective is to forecast granular power outage risks, encompassing the spatial extent of outages, the duration of extreme events, equipment failure probabilities, and the expected outage duration^[64]. The pursuit of short-timescale risk prediction can accommodate the scheduling needs of emergency management departments for accurately pre-positioning repair crews and materials before disasters. Through feature engineering, addressing data imbalance, and ensemble learning, we enhance prediction accuracy and model performance^[65]. This topic exemplifies a paradigm shift in grid disaster prevention from a reactive posture to a proactive early warning strategy, aiming to mitigate power interruptions through early forecasting. The transformation of early warning modes enables grid enterprises to optimize emergency resource allocation, comply with regulatory mandates, and mitigate adverse social consequences.

3.2.1.7 Topic 6: Power forecasting

As shown in Figure 7(a), Topic 6 focuses on enhancing the accuracy of short-term forecasting for wind power and load demand under extreme weather conditions. Its core lies in developing specialized high-precision models and methods tailored for different forecasting targets. To address the key challenges of data scarcity and high volatility in wind power and electricity load data during extreme weather, studies widely employ data augmentation techniques to generate high-quality synthetic data, effectively resolving the small-sample learning problem in short-term forecasting^[66]. Improving forecasting accuracy under extreme conditions is primarily aimed at meeting the rigid safety constraint requirements of power grid dispatch departments to maintain power supply and demand balance in real-time operations. In terms of model architecture, research has designed complex hybrid models capable of simultaneously processing wind power, photovoltaic power, and load demand. These models utilize advanced techniques such as attention mechanisms to precisely capture the dynamic characteristics of different forecasting targets under extreme conditions^[67]. Furthermore, research has been pivotal in driving the paradigm

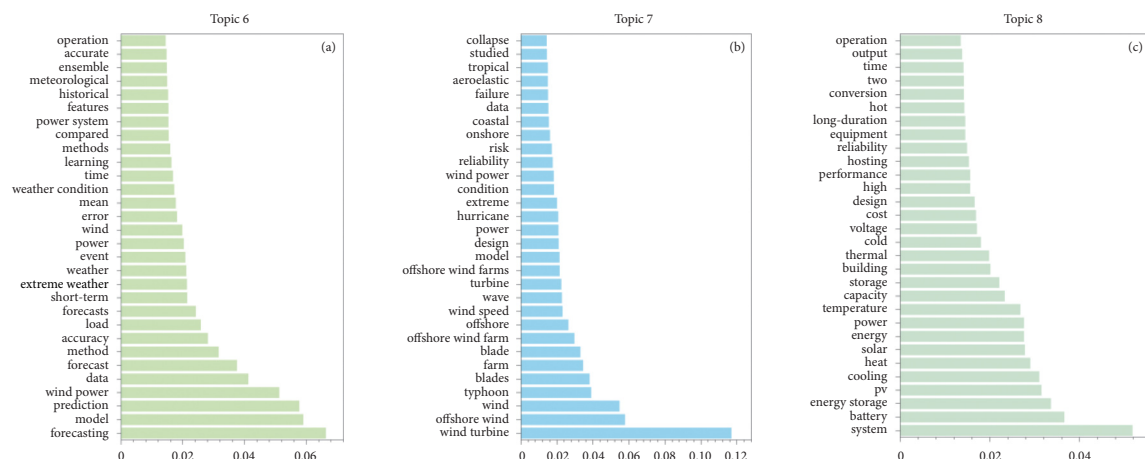


Fig. 7 Keyword distribution and scores. (a) Topic 6, (b) Topic 7, (c) Topic 8.

shift from deterministic to probabilistic forecasting. This approach generates predictive outcomes for targets such as wind power and load that incorporate quantifiable uncertainty intervals. Consequently, it substantially enhances the practical utility of forecasts for robust decision-support and proactive risk management^[68]. Finally, comprehensive evaluations under various extreme weather scenarios demonstrate that, compared to conventional models, these methods achieve higher accuracy and robustness across multiple forecasting targets, including wind power, photovoltaic power, and load demand^[67].

3.2.1.8 Topic 7: Wind power facility vulnerability

As shown in Figure 7(b), Topic 7 is similar to Topic 4, but specifically focuses on offshore wind power facilities. Research in this area centers on structural safety analysis and design optimization under typhoon action. First, studies utilizing computational fluid dynamics and finite element analysis elucidate critical phenomena such as blade vibration lock-in and tower buckling failure under extreme wind speeds^[69]. Second, extensive investigations into typhoon-resilient strategies have led to advancements in cut-out control based on combined wind speed-time thresholds, blade chordwise slot optimization to mitigate loads, and typhoon-resistant yaw control systems^[70]. Third, reliability assessment under combined typhoon and wave action has emerged as a critical focus, involving joint probability models, load calibration, and time-varying failure rate models for offshore wind farms^[71]. Finally, research into farm-typhoon interactions suggests that large-scale offshore wind farms may alter the lower atmosphere's dynamic structure, potentially reducing typhoon wind speed and shifting precipitation centers^[72].

3.2.1.9 Topic 8: Multi-energy hybrid system optimization

As indicated in Figure 7(c), the keyword cluster for Topic 8 encompasses core components (battery, energy storage, photovoltaic, solar, thermal), operational objectives (reliability, cost, performance, hosting capacity), and application scenarios (building, high-temperature environment). This topic places particular emphasis on the roles of photovoltaic (PV) systems, battery energy storage systems (BESS), hydrogen energy storage

(HES), and thermal energy storage in enhancing overall system reliability, operational flexibility, and resilience^[73,74]. The increasing penetration of renewable energy introduces multiple challenges for the system. In this context, energy storage systems serve not only as a crucial means to smooth power fluctuations and enable energy time-shifting, but also play a central role in maintaining grid stability, enhancing power supply reliability, and participating in ancillary services^[74,75]. Furthermore, intelligent control strategies, such as model predictive control and game-theoretic optimization^[76], alongside capacity configuration optimization models like multi-objective stochastic-robust programming, have been extensively incorporated^[77]. Notably, research has further investigated the integration potential of rooftop photovoltaic systems and hybrid energy storage within microgrids, targeting both urban building clusters and remote off-grid areas. Analyses extend to their thermoelectric coupling effects under varying climatic conditions and the subsequent impact on the local microclimate^[77,78]. Future distributed energy planning is transcending the boundaries of the power system alone and evolving toward the coordinated management of integrated energy and the ecological environment.

3.2.1.10 Topic 9: Advanced real-time decision-making methods

As shown in Figure 8(a), the research paradigm for power system resilience in Topic 9 is shifting from traditional, deterministic model-based optimization towards a novel paradigm characterized by data-driven approaches, adaptive modeling, and intelligent decision-making. Traditional model-driven approaches confront fundamental limitations, as they are often characterized by high computational complexity and an inherent lack of learning capability^[79]. To address these challenges, the prevailing research paradigm is shifting towards data-driven deep reinforcement learning. This methodology typically involves formulating the complex restoration and control problems under extreme weather events as a Markov Decision Process^[80]. Furthermore, by developing frameworks such as hybrid multi-agent deep reinforcement learning, distributed energy resources can be modeled as cooperative agents, enabling their effective coordination^[81]. Extensive case studies have validated the superior

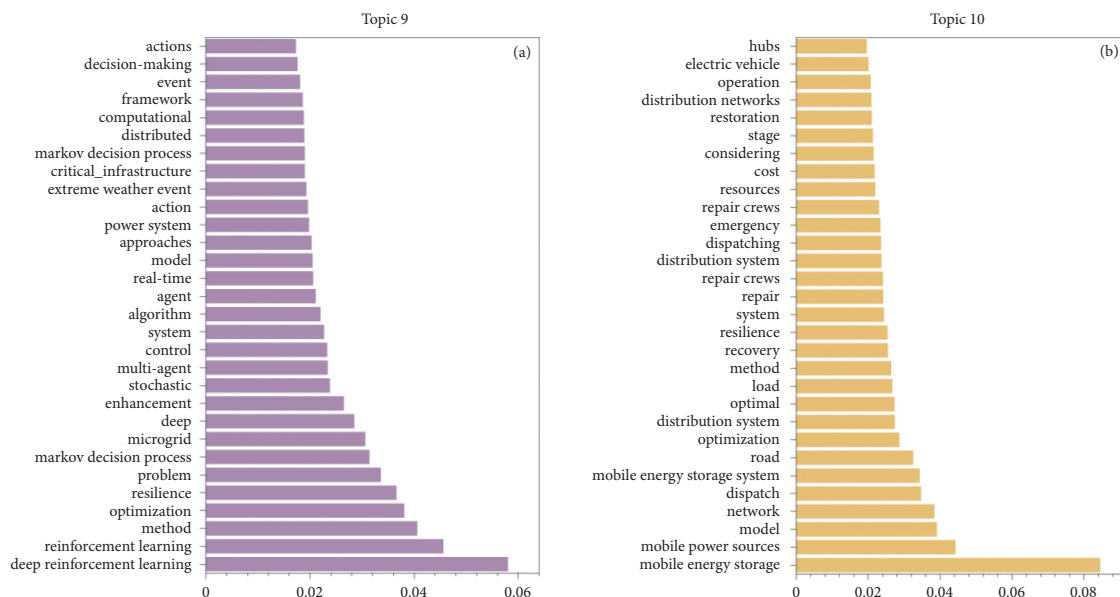


Fig. 8 Keyword distribution and scores. (a) Topic 9, (b) Topic 10.

performance of this approach. In terms of decision-making efficiency, it achieves real-time responsiveness by reducing computational time from 56.655 seconds to 0.012 seconds^[82]. Regarding restoration effectiveness, it demonstrates a remarkable reduction in load loss, achieving a 95.7% decrease in load shedding losses^[83].

3.2.1.11 Topic 10: Mobile energy storage and emergency resource dispatch

As illustrated in Figure 8(b), to address the challenges posed by extreme events to distribution networks, a core focus of current research lies in the optimal coordination of distributed mobile resources (DMRs), such as repair crews (RCs), mobile energy storage systems (MESS), and electric vehicles (EVs). Extreme weather events often result in large-scale damage to fixed grid infrastructure, making it difficult to meet the flexible emergency response needs of complex disaster areas by relying solely on traditional static backup power sources. This coordination aims to achieve both rapid grid recovery and enhanced system resilience. This research direction signifies an important evolution from traditional scheduling methods towards an integrated coordination paradigm for repair crews, electric vehicles, and renewable energy sources. An application is a strategy that enhances distribution network resilience against extreme events by utilizing MESS. This strategy involves deploying MESS to provide temporary power supply to critical loads before repair crews complete permanent physical repairs, thereby formulating an efficient recovery strategy^[84]. This integrated approach is underpinned by two key methodological innovations. Firstly, research has evolved from static optimization to multi-stage stochastic programming models. These models are designed to explicitly capture the temporal evolution and inherent uncertainties of the post-disaster restoration process^[42]. Secondly, there has been a shift from modeling the power system in isolation towards a coupled transportation-power grid analysis^[85].

3.2.2 Dynamic evolution of topic

Topic 0 dominates with 630 papers, reflecting sustained attention to methodologies and framework development for assessing power system resilience under extreme weather. The concentrated research on this topic mainly stems from the need of government regulatory agencies for a unified standard to measure the disaster resilience of power systems. Topic 1 and Topic 2 rank second and third with 364 and 203 papers respectively, indicating that cross-disciplinary research on climate risks and energy transition is a current hotspot. This popularity arises from the carbon reduction policies that drive large-scale integration of new energy sources, which leads to increased system vulnerability under extreme weather. Consequently, grid managers are compelled to study the actual impacts of climate change on energy security. Publications on Topic 3, Topic 4, and Topic 5 all exceeded 100, highlighting broad interest in the technical application layer. In contrast, Topic 9 had only 36 papers, and Topic 7 had just 57 papers. The main reason is that introducing new technologies such as deep reinforcement learning and typhoon-resistant offshore wind power into practical grid management requires lengthy safety validation and pilot approval processes. As a result, there is a certain lag in policy implementation. Although these topics are in their early stages, they represent cutting-edge research directions.

Figure 9 provides a more granular perspective on the evolutionary dynamics of each topic. Viewed through a temporal

lens, the research activity exhibits distinct phasic characteristics. The period from 2001 to 2010 represents the initial phase, during which the publication output for all topics was generally low. Only sporadic research activity was observed, primarily in Topic 0, Topic 1, and Topic 3. This is mainly because the power industry at that time focused primarily on routine power supply. Extreme weather was largely regarded as a force majeure natural disaster, and had not yet been incorporated into the regular scope of work requiring proactive defense. The period from 2011 to 2018 marks a phase of rapid development, characterized by exponential growth in publication output across all topics. Among these, the growth of Topic 0 was most pronounced, increasing from 7 publications in 2011 to 119 in 2018. The research explosion during this phase was primarily driven by the occurrence of numerous large-scale blackouts caused by extreme weather. These incidents prompted adjustments to relevant safety regulations, which mandated enhancements in the disaster prevention capability of power grids. The period from 2019 to the present is characterized by consolidation and maturation, with research intensity having largely stabilized. Publication output reached its peak in 2024 at 364 articles, primarily driven by Topic 0.

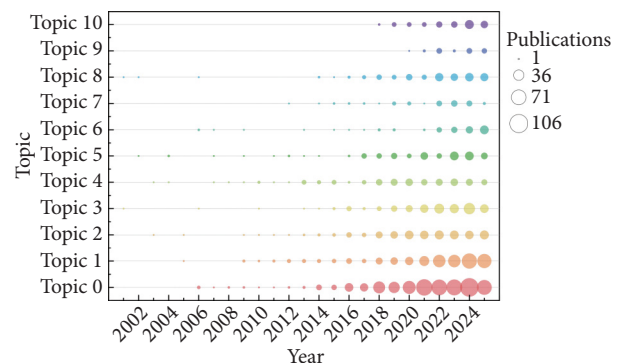


Fig. 9 The annual publications by topic.

An analysis of the topic evolution reveals that early-stage research predominantly focused on fundamental issues, such as those encompassed by Topic 0 and Topic 4. During the intermediate phase, application-oriented research topics, including Topic 1, Topic 2, and Topic 5, experienced rapid emergence. More recently, emerging research directions characterized by technological convergence have gained prominence, notably Topic 9 and Topic 10. This shift from fundamental research to applied research and then to technological convergence reflects an escalating demand for addressing extreme weather. It is no longer sufficient to rely solely on theoretical analysis; instead, there is an urgent need for automated and intelligent tools that can be implemented to solve practical problems. It is particularly noteworthy that research activity across all topics has reached historically high levels since 2020. This is because the frequency and destructive power of extreme weather events in recent years have far exceeded those of the past, repeatedly testing existing defense measures and thereby accelerating all research directions from basic assessment to cutting-edge technology applications in search of more effective response strategies.

3.2.3 Topic clustering framework

Based on the 11 research topics generated by the BERTopic model, this study calculates the similarity between each pair of topics. By combining the topic similarity scores with the stages of

extreme weather events, the 11 topics are integrated into a research framework for power systems under extreme weather, as presented in Figure 10. Although this framework follows the temporal dimension of “pre-event prediction and assessment–during-event real-time control–post-event recovery dispatch”, its

core has undergone a fundamental paradigm shift: from passive defense driven by a single physical mechanism to proactive resilience shaping characterized by data-driven approaches and cross-system collaboration.

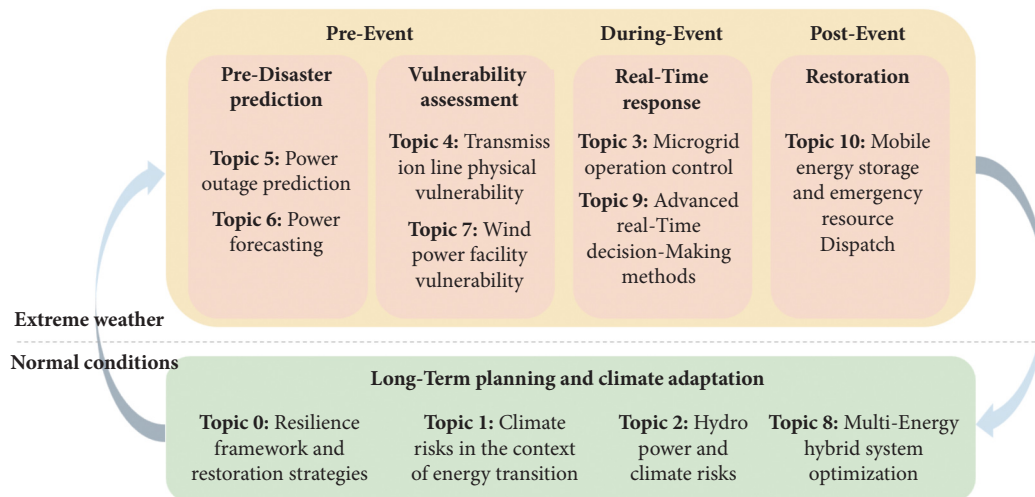


Fig. 10 Research framework for power systems under extreme weather.

This shift is first grounded in long- and medium-term planning and adaptation. Strategic foundational research, represented by resilience frameworks and assessment (Topic 0), occupies a dominant position. Long-term planning themes, such as climate risk in the context of macro energy transition (Topic 1) and climate risk for hydropower systems (Topic 2), also constitute research priorities. These topics not only focus on current system vulnerabilities but also emphasize the incorporation of future climate scenarios and energy transition trends into infrastructure planning and investment decisions. This reflects the urgent academic need to build a forward-looking, systemic resilience system. It indicates that power system resilience research has moved beyond mere technical improvement, rising to a strategic level deeply integrated with energy structure transformation, water resource management, and climate change adaptation. The new paradigm requires the implementation of data-driven and cross-system collaboration concepts throughout the entire lifecycle. This macro-level, long- and medium-term strategic planning simultaneously needs to be materialized through micro-level, precise technical responses across the full lifecycle of extreme weather events.

At the technological frontier, research directions are evolving precisely along the timeline of extreme weather events, demonstrating a fundamental paradigm shift from “traditional physical mechanism-driven” to “data-driven and cross-system collaboration”. In the pre-event stage, research focuses include the physical vulnerability assessment of transmission lines (Topic 4) and wind turbines (Topic 7). Meanwhile, machine learning-based outage prediction (Topic 5) and power forecasting (Topic 6) have completely broken through the limitations of traditional physical-statistical models, which suffer from poor generalization under extreme scenarios. In the during-event stage, operational strategies based on microgrid control (Topic 3) are gradually evolving towards autonomous decision-making systems driven by deep reinforcement learning (Topic 9). This model-free, adaptive

decision-making mechanism overcomes the computational curse of dimensionality inherent in traditional mathematical optimization, achieving a leap in during-event control from “physical model solving” to “data-driven intelligent decision-making”. In the post-event stage, research on mobile resource dispatch (Topic 10) transcends the boundary of a single power system, innovatively integrating transportation networks with power systems to construct a multi-stage collaborative restoration model that accounts for spatiotemporal constraints of road networks. Multi-energy complementary system optimization (Topic 8) serves as a technical support across all stages. It integrates energy storage and renewable energy through data-driven coordinated optimization algorithms, effectively mitigating system risks arising from the variability of wind and solar power (Topic 1) and the uncertainty of hydropower (Topic 2). This integrated framework shows that the classic “pre-during-post” resilience framework is no longer confined to traditional physical mechanisms and isolated responses. It is reshaped into a complex systems engineering project that is data-driven, linked by cross-system collaboration, and deeply coupled with climatic factors.

4 Conclusion and research outlook

4.1 Conclusion

Enhancing the resilience of power systems under extreme weather is of critical importance for ensuring their secure and stable operation. This study provides a bibliometric analysis of research developments in this field from 2001 to the present and employs the BERTopic model to identify prevailing research topics. The principal conclusions of this work are summarized as follows: (1) Temporally, the field has evolved through distinct phases: a slow inception period (2001–2010), followed by a phase of moderate growth (2011–2015), and subsequently an accelerated expansion phase (2016–present). (2) In terms of the distribution of research

efforts, the United States and China hold dominant positions in leading the field. Their institutional collaboration networks have established a pattern centered on these two nations with international synergy, wherein organizations such as the United States Department of Energy and the State Grid Corporation of China play pivotal roles. (3) Topic modeling identified 11 core research topics. Among these, Resilience Frameworks and Assessment, Climate Risks in the Context of the Macro Energy Transition, and Hydropower and Climate Risks constitute the three central pillars of current research. (4) This study constructs a classification framework that integrates temporal sequencing with system states, revealing a profound paradigm shift from reactive emergency response towards proactive resilience building within the field.

This study conducts a bibliometric analysis of research on power systems under extreme weather conditions; however, several limitations remain. First, the literature search was conducted solely within the Web of Science database and restricted to English-language publications, which may have led to the omission of some relevant studies, particularly important non-English or regional research. Future research could incorporate additional databases to achieve more comprehensive coverage and analysis. Moreover, topic modeling relies exclusively on abstracts, thereby precluding the incorporation of full-text content, which may result in an incomplete topical extraction. Subsequent research could extract other parts of relevant articles, such as models or conclusions, to enhance the depth of thematic analysis.

4.2 Research outlook

Based on the 11 core topics identified in this study, future research should prioritize the following three directions:

(1) Developing Systematic Resilience Assessment Frameworks and Climate Risk Planning. Future research must transcend the limitations of single physical dimensions. It is imperative to construct a refined, quantitative resilience assessment system that encompasses multi-spatiotemporal scales across “source-grid-load” interactions (Topic 0). Furthermore, compound extreme scenarios such as “energy droughts” induced by climate variability must be endogenously integrated into the long-term evolutionary pathways of macro-energy transitions (Topic 1) and hydro-wind-solar multi-energy complementary scheduling models (Topic 2). This integration is crucial for revealing the supply-demand imbalance mechanisms within the climate-energy nexus, thereby driving the paradigm shift of power systems from passive post-disaster response to proactive, forward-looking defense.

(2) Advancing Data-Driven Intelligent Forecasting and Real-Time Decision-Making. Given the challenges of data scarcity and high stochasticity under extreme scenarios, future efforts must prioritize overcoming the bottlenecks in cross-sectoral data sharing between meteorological and power grid systems. It is essential to develop spatiotemporal evolution forecasting of power outage risks (Topic 5) and source-load power forecasting capabilities (Topic 6) based on a hybrid approach integrating physical mechanisms and data-driven methods. Additionally, the application of algorithms such as deep reinforcement learning in complex and uncertain environments requires further in-depth exploration (Topic 9). These advancements will propel system dispatch from traditional deterministic optimization toward a highly adaptive, distributed, and intelligent real-time decision-making paradigm.

(3) Promoting Multi-Energy Synergistic Microgrid Construction and Cross-Infrastructure Network Coordinated

Recovery. Future research should focus on the synergistic integration of microgrid control (Topic 3), multi-energy complementary optimization (Topic 8), and mobile emergency resource dispatch. A critical priority is to solve the spatiotemporal coordinated dispatch of mobile emergency resources and the mechanisms of network topology reconfiguration within coupled transportation-power networks (Topic 10). By accounting for transportation network constraints and multi-objective game dynamics, researchers can achieve the global optimal configuration of cross-system heterogeneous resources, ultimately balancing resilience and economic efficiency during extreme disasters.

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Author contribution statement

Tao Lv: Supervision, Funding acquisition, Formal analysis. Xiangyun Meng: Writing – original draft, Methodology, Conceptualization, Funding acquisition. Xingyu Wang: Data curation. Cong Li: Investigation. Xiuzhu Zang: Validation. Xu Deng: Investigation. Xiaoran Hou: Visualization, Software. Jie Xu: Funding acquisition.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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