Power System Resilience During 2001-2022: A Bibliometric and Correlation Analysis

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Abstract: Research on power system resilience has increased due to frequent natural hazards. Many reviews have been performed on power system resilience, focusing on specific topics such as the application of energy storage systems and microgrids for resilience enhancement. To comprehensively analyze the work carried out on power system resilience, this paper presents a methodology to perform quantitative analyses that combines bibliometric and correlation analyses. For this reason, 851 research publications from popular databases, namely Scopus and Web of Science, spanning from 2001 to 2022, were obtained for analysis. In the quantitative analysis, bibliometric measures are evaluated and analyzed to identify the most productive elements (e.g., countries, papers, journals, and institutions), keyword co-occurrences, and track the thematic evolution of authors' keywords. Additionally, hazard metrics such as risk against natural hazards and word count of natural hazards are proposed to reflect the event-specific risk level of a country and its progress in event-specific resilience research. These metrics are later utilized to perform correlation analyses along with bibliometric measures. This correlation aims to identify lesser-explored natural hazards and countries with the potential for event-specific resilience studies. Overall, this study offers insights into power system resilience trends and emerging areas. It emphasizes less-attended, highly exposed natural hazards, helping prioritize research for future resilient models to address their unique challenges.

Keywords: *Bibliometric analysis, Climate change, Co-occurrence analysis, Modern power system, Natural hazards, Power system resilience*

Word Count: 9325 words

Abbreviations:

AAC	Average Article Citation	RII	Research Impact Index
ATCpA	Average Total Citations per Article	RNH	Risk against Natural Hazards
ATCpY	Average Total Citations per Year	TC	Total Citations
CVaR	Conditional Value at Risk	TCpY	Total Citations per Year
GRNH	Global Risk against Natural Hazards	TNP	Total Number of Publications
NHWC	Word Count of Natural Hazards	YP	Year of Publication

1. Introduction

Natural hazards have severely damaged economies in recent years, especially critical infrastructures like power grids. The resulting outages have adverse effects on people's livelihoods [1]. Climate change predictions predict natural hazards may increase, leading to potentially catastrophic damage to the already aging power system [2]. In response to these challenges, several methodologies are proposed in the literature that model and integrate specific natural hazards, such as windstorms and earthquakes, into the resilience enhancement framework. These methodologies are intended to strengthen grid resilience against these hazards [3]–[5]. While several reviews in the literature summarize resilience studies, most of them are confined to specific topics within the realm of power system resilience.

In the literature, several studies have proposed different methodologies that could contribute to a gradual improvement in the resilience trapezoid curve. The primary aim of these methodologies is to enhance either infrastructural resilience (e.g., having redundant or hardened systems) or operational resilience (e.g., using prior installed sectionalizers to bypass failed equipment), or both. The operating condition of the power system is monitored and controlled by protection devices. These devices are typically installed at various points in the power system, such as at substations, on transmission lines, and at transformers. As a rule, these devices are connected to a control system that coordinates their operation and maintains stability and reliability. Before 2001, resilience studies focused on the survivability of power systems under any type of disturbance without explicitly mentioning the term *power system resilience* [9]. In the early stages of resilience research, novel protection schemes were introduced to enhance the performance of an interconnected system during an unforeseen event [10], [11]. Even though protective devices maintain the stability of the system, a cascading failure, specifically in the transmission network, could potentially lead to a total or partial blackout. Since flexible AC transmission system devices like unified power flow controllers can extend the operating limits of transmission lines to their thermal limits, these devices are proposed to enhance system resilience against cascading failures in transmission networks [12].

Meanwhile, the introduction of distributed renewables into the power system has raised the concept of decentralized power systems and thereby led to various studies on distributed energy resources and microgrids. Many studies have investigated the possibility of microgrids for resilience enhancement against emergency conditions such as utilizing its energy resources via multi-agent control, optimal scheduling of its resources, and optimal placement of microgrids across the network [13]–[15]. Before 2013, most research work on power system resilience focused on disturbances, not specifically on natural hazards. K.

Barker *et al.,* initially coined this and proposed a methodology based on loss of branch (like N-1 contingency security analysis) to quantify the potential impact on system resilience [16]. Later, Panteli *et al.,* proposed a generalized metrics and quantification methodology for both infrastructural and operational resilience based on a conceptual resilience trapezoid that depicts system performance before, during, and after the event (like Figure 1) [8], [17]. In 2014, an infrastructural resilience strategy that strengthened the capacity of previously installed generators is developed [18]. In addition, network component reinforcement is performed with the goal of improving system resilience. Since improving infrastructural resilience involves a substantial budget, several studies have been performed with various optimization models that can minimize investment. Similarly, [19] suggested that battery energy storage systems can be transported via rail to reach the areas affected by natural hazards and enhance system resilience. Additionally, several studies proposed different optimization and techno-economic models for various infrastructural resilience measures, such as upgraded lines, backup generators, battery energy storage systems, etc., [20]–[24].

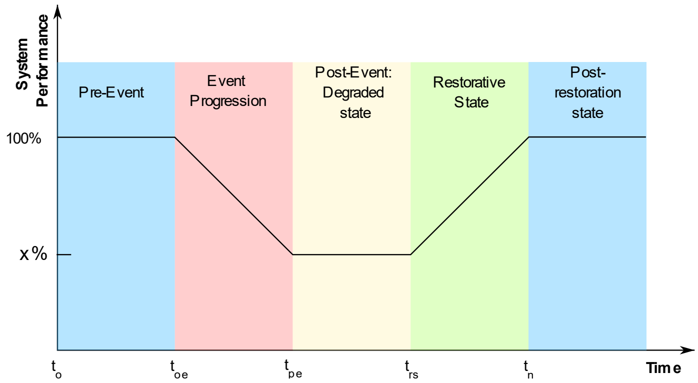

Figure 1. Resilience Trapezoid Representing System Performance [8].

During the early 2010s, methodologies were proposed for improving infrastructural resilience that either assumed the impact (e.g., failures) randomly or analyzed N-k contingencies. Some studies have used the conventional contingency security methodology and developed a synthetic failure database using machine learning algorithms, while some have applied machine learning to derive system vulnerability against disasters [25], [26]. Meanwhile, few research works have proposed stochastic optimization models based on fragility-driven modeling. These models determine the failure probability of components against natural hazards such as windstorms and earthquakes [27]–[29]. Similar to infrastructural resilience, various optimization models were developed to improve operational resilience by optimal placement of sectionalizing switches, optimal scheduling of prior installed distributed energy resources via network reconfiguration, networked microgrids, defensive islanding, electric vehicles as emergency backup, etc., [30]–[35]. Recently, optimization models that perform optimal sizing, pre-positioning, and routing of mobile energy resources are being implemented to increase power system resilience [36]–[40]. Furthermore, most resilience methodologies follow expected energy not served to quantify resilience. As natural hazards can be characterized as high-impact low-probability events, the expected energy not served derived from stochastic models might not enhance resilience as intended [3]. As a result, recent studies proposed risk-aware optimization models that minimize the conditional value-at-risk (CVaR) to identify the potential location of distributed generators, which will improve system resilience [41]. Moreover, resilient systems have been expanded to encompass cyber-physical systems, where the restoration time of these systems can be minimized with the help of additional infrastructure [42].

During the period from 2001 to 2022, there were more than 800 research publications related to power system resilience, published in several journals and conference proceedings. Among these, there are more than forty publications that review studies performed in this field, mostly restricted to a specific perception. For example, [6] presented a comprehensive review of various definitions of power system resilience, metrics to quantify resilience, optimization methods for infrastructural and operational resilience enhancement strategies, and proposed their challenges and future directions. However, this paper focuses on resilient power system planning. Other research works focus on vulnerability assessment, also known as the estimation of outage-prone nodes against natural hazards, the application of machine learning related to resilience, and the quantification of cyber-physical power systems [43]–[46]. Furthermore, some studies explored various metrics and quantification methodologies related to system resilience [47], [48]. The summary of the latest reviews in the field of power system resilience, highlighting their focus area, the methodology employed for reviewing, and the type of hazards investigated, is presented in Table 1. Most reviews adopt a conventional approach, conducting systematic reviews, literature reviews, or state-of-the-art reviews, which concentrate on specific research areas within power system resilience, drawing from a selected set of resources. In contrast, a bibliometric approach or bibliometric analysis provides a comprehensive overview and quantitative representation covering the entire field.

TABLE 1. SUMMARY OF RECENT REVIEW ARTICLES IN THE FIELD OF POWER SYSTEM RESILIENCE.

Ref	Journal	Title	Focus Area	Review Methodology	Hazard Type
[49]	Renewable and Sustainable Energy Reviews	Trends in modern power systems resilience: State-of-the-art review	Resilience planning via smart grids and multi-microgrids	State-of-the-Art	Generic

[46]	Renewable and Sustainable Energy Reviews	A systematic review on power system resilience from the perspective of generation, network, and load	Impact analysis and quantification in power system resilience	Systematic review	Earthquakes, Heatwave, Windstorm, and Flood
[47]	IEEE Systems Journal	A Review of the Measures to Enhance Power Systems Resilience	Resilience quantification	Literature review	Generic
[50]	IET Energy Systems Integration	Resilience assessment methodologies and enhancement strategies of multi-energy cyber-physical systems of the distribution network	Planning and Operation in Multi-energy cyber-physical system	State-of-the-Art	Windstorm
[51]	Sustainable Cities and Society	Resilience Enhancement Strategies For and Through Electric Vehicles	Electric Vehicles	Literature review	Generic
[52]	Renewable Energy	A comprehensive overview of modeling approaches and optimal control strategies for cyber-physical resilience in power systems	Resilient control strategies	Systematic review	Generalized Disaster and Cyberattacks
[53]	IEEE Access	Microgrids and Resilience: A Review	Microgrids for resilience enhancement	Literature review	Hurricanes
[54]	Energy Strategy Reviews	Integrated water-power system resiliency quantification, challenge and opportunity	Integrated water-power system	Literature review	Generic
[55]	Renewable and Sustainable Energy Reviews	Quantitative analysis of power systems resilience: Standardization, categorizations, and challenges	Resilience quantification	Systematic review	Windstorms

[56]	IET Energy Systems Integration	Resilient distribution system leveraging distributed generation and microgrids: a review	Distributed generation and microgrids for resilience enhancement	State-of-the-Art	Generic

A bibliometric study is a statistical approach that analyzes the publications and citation patterns of the scientific literature and the impact of research publications. Additionally, this type of study is often used to assess the productivity and impact of research groups, institutions, or individual researchers, as well as identify trends in chosen research fields. For instance, there are bibliometric studies on power system planning in [57], deep learning applied to smart grids in [58], and energy storage systems in microgrids in [59]. Therefore, to derive the trend of future directions in power system resilience, it is useful to perform bibliometric analyses related to this field. Since the methodologies developed to enhance power system resilience are heavily dependent on the type of natural hazards, performing only bibliometric analyses may not answer questions such as 1) Which type of natural hazard is commonly studied? 2) Which countries focus on what type of hazard? 3) How many research publications propose methodologies for specific events? Therefore, simply identifying research trends and hotspots in power system resilience may not be sufficient. Hence, it is essential to identify solutions that might help researchers shift their focus to resilience research. To address this, it is crucial to derive a correlation between bibliometric measures and natural hazard risk. This will enable us to further understand the trend and explore possible future directions in power system resilience.

In line with this discussion, this paper proposes a novel methodology that combines bibliometric and correlation approaches. The major contributions resulting from this proposed methodology are as follows:

1. An analysis of bibliometric data is performed to identify the most productive countries, institutions, journals, and most cited research publications.
2. Analyze keywords co-occurrence and thematic evolution of authors' keywords to determine research trends and visualize co-occurrence and evolution using a network diagram and a Sankey diagram.
3. Determine which countries have a high scope for resilience research based on the number of publications, citations, percentage of the population vulnerable to natural hazards, and the exposure level to natural hazards.

4. Determine which natural hazards have been the most investigated, from 2001 to 2022, as well as the top countries that produced focused research publications on that natural hazard.

The results presented in this paper can help researchers and engineers in power system resilience to better understand trends, emerging areas, and lesser-explored natural hazards, as well as the countries mostly affected by these hazards. The rest of the paper is organized as follows: the methodology applied in this paper to perform the quantitative analysis is elaborated in Section II. The quantitative analysis results are discussed in Section III and the paper is summarized with conclusions in Section IV.

2. Methodology and Assessment Framework

The methodology applied in this paper to perform quantitative analysis, which includes a bibliometric and correlation approach, is illustrated in Figure 2. The framework involves collecting and processing data about research publications and natural hazards, facilitating quantitative analysis. This section outlines and elaborates on the major stages of the proposed methodology in the following subsections.

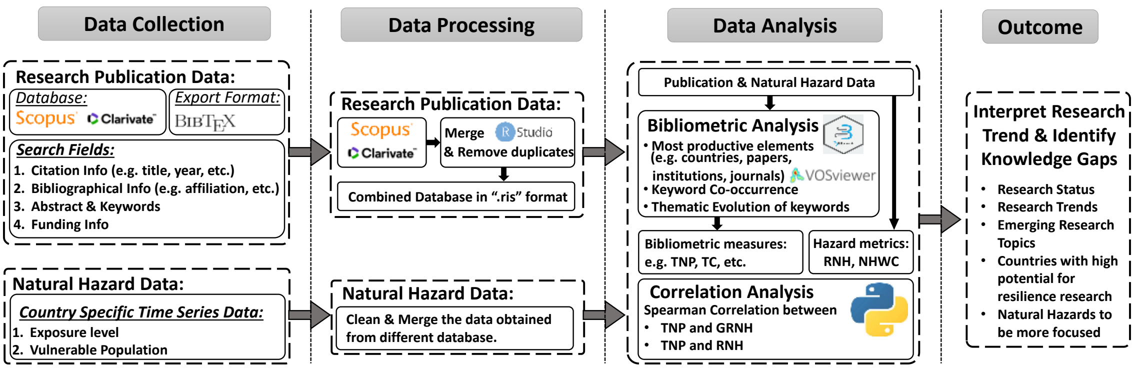

Figure 2. Proposed Methodology for Quantitative Analysis.

2.1 Data Collection and Processing

The research publication data required to perform the quantitative analysis (shown in Figure 2) is obtained from two popular databases: Scopus and Web of Science, as most peer-reviewed publications are indexed in either of them. The data collected from these databases includes citation information such as the title of the research publication, year in which it was published, type of publication (e.g., original research, review, conference proceeding, etc.), number of citations, etc., bibliographical information such as affiliation, publisher, etc., abstract, authors' and index keywords, and funding details.

The strategy for searching this data involves looking for search words or topics in the title, abstract, and keywords of the research publications. The search words or topics applied in this study are: ("power-system-resilience OR power-system-resiliency OR distribution-system-resilience OR power-system-operational-resilience OR impact-on-system-resiliency OR power-system-hardening OR impact-on-system-resilience OR distribution-system-resiliency OR distribution-system-hardening OR transmission-system-resilience OR transmission-system-hardening OR power-system-survivability OR high-impact-low-probability-events OR resilience-based-planning OR resilience-based-power-system-planning OR resilience-based-restoration OR power-grid-resilience OR power-grid-resiliency OR power-grid-operational-resilience OR microgrids-resilience OR microgrids-resiliency"). This data is obtained in *'.bib' format* which will be further utilized for data processing. Since research on power system resilience is relatively new, data relevant to this field appeared in the database from 2001. Therefore, the period chosen for this study is from 2001 to 2022. Once the research publication data is obtained from the databases, it is merged and cleaned before further analysis. For instance, duplicates must be removed to create a consolidated dataset for further analysis. Additionally, when analyzing keywords, titles, and abstracts, various forms of expressions, such as abbreviations, singular and plural, and synonyms, should be unified.

The dataset on natural hazards comprises vital information on hazard exposure and its impact on vulnerable populations. Country-specific time series data was meticulously collected from reputable sources like Bündnis Entwicklung Hilft and GWIS [60], [61]. The data covers a wide range of natural hazards, including earthquakes, tsunamis, various types of floods (coastal, riverine, and sea level rise), windstorms (hurricanes, typhoons, and cyclones), and wildfires in more than 190 countries. Once different hazard data is obtained from different databases, it is merged and cleaned to represent the same countries from both databases.

2.2 Data Analysis

In this section, an initial description of several metrics employed in this paper to conduct the quantitative analysis and their significance is provided. Subsequently, the procedures for the quantitative methods applied to analyze the data are elaborated, encompassing bibliometric analysis for identifying the most productive elements, exploring keyword co-occurrence, and understanding the thematic evolution of keywords. Further, the correlation analysis procedure is detailed.

2.2.1 Metrics and their Significance

To perform quantitative analysis, this study considers several bibliometric measures, including total citations (TC), total citations per year (TCpY), total number of publications

(TNP), average article citation (AAC), average total citations per article (ATCpA), average total citations per year (ATCpY), H-index, G-index, M-index, and research impact index (RII). Additionally, the hazard metrics proposed in this study encompass risk against natural hazards (RNH), which is specific to each country, global risk against natural hazards (GRNH), a derivative of RNH, and word count of natural hazards (NHWC). These hazard metrics will provide insights into a country's risk level and its progress in resilience research. In this paper, the RNH values for specific natural hazards, such as earthquakes, tsunamis, floods, windstorms, and wildfires are represented as RNH_{EQ}, RNH_{TS}, RNH_{FL}, RNH_{WS}, and RNH_{WF}, respectively. Similarly, the GRNH is also represented for each natural hazard.

A steady increase in TC, TCpY, and TNP indicates that the chosen field of research has gained significant importance. The AAC is a country-wise metric used to calculate the average citations of articles authored by a specific country. ATCpA and ATCpY are year-wise metrics, where ATCpA is the ratio of the total citations to the total number of articles published in a specific year and ATCpY is the ratio of ATCpA to the number of citable years. In general, a rise in ATCpA can be seen as a positive development. This is because it suggests that research published in a specific year is having a significant impact and is being widely recognized and utilized by other researchers. Having high values of ATCpA and ATCpY can indicate that a body of work is significant and influential in a particular field of research. Additionally, having these metrics over a longer period can suggest that the research is enduring and has had a lasting impact. The definitions of the various indexes are as follows: H-index is defined as the number of published papers (N) that have been cited N or more than N times; M-index is the H-index per year since its first publication; G-index is defined as the largest number such that the top G articles received (together) at least G^2 citations; RII is defined as the ratio of TC to TNP. The higher the value of these indexes, the greater the impact created.

The risk metric RNH for each country is calculated based on the IPCC risk framework, which combines exposure and vulnerability [62]. In this context, exposure refers to the level or intensity of a natural hazard. For example, earthquakes may be measured as peak ground acceleration of 0.1 g or higher. The framework takes an inclusive approach to situations where risk is applied. For instance, if a population relocates under normal circumstances, this displacement cannot be categorized as a vulnerable population. However, during any natural hazard, such a statement may become more relevant and appropriate to determine risk. Therefore, in this paper, vulnerability to natural hazards is derived from the internal displacement of people caused by these natural hazards. Considering this concept, the RNH is calculated using equation (1) [63].

$$RNH = \sqrt{Exposure \times Vulnerability} \qquad (1)$$

It is straightforward that the higher the value of RNH or GRNH, the greater the risk. It is worth noting that RNH values for specific natural hazards are calculated based on corresponding values of exposure and vulnerability. The metric GRNH refers to global risk, which is calculated by adding RNH values for all countries. The NHWC specifies the word count value of a particular hazard (e.g., earthquakes, floods, tsunamis, etc.) that occurs in the title, abstract, and keywords of research publications. To ensure consistency in monitoring natural hazard data, the NHWC for floods incorporates information regarding coastal events, riverine incidents, and sea level rise. Meanwhile, the NHWC for windstorms integrates data pertaining to hurricanes, typhoons, and cyclones. Furthermore, based on the NHWC, research publications specific to each natural hazard are derived and represented similarly to the RNH. For example, the TNP (derived from NHWC) for earthquakes is denoted TNP_{EQ}. In this process, a simple word count may not accurately reflect the TNP of a specific hazard. This is because articles might discuss and mention multiple natural hazards in their abstracts to establish a common context, and then specify the natural hazard of interest in both the abstract and keywords. Therefore, this paper proposes a method to derive event-specific TNP from NHWC by considering keywords corresponding to natural hazards present either in the title OR in the abstract AND keywords section (including authors' OR index keywords). This approach ensures high accuracy in capturing articles related to a particular natural hazard, as it considers not only the presence of relevant keywords but also their strategic placement within the publication. A Python code is developed to obtain the value of NHWC for all-natural hazards and their corresponding research publications (e.g., TNP_{EQ}), from the combined database.

2.2.2 Quantitative Methods

To analyze the processed data, bibliometrics, and correlation analysis are applied in this paper. The steps followed in the bibliometric analysis are 1) Data collection and processing, 2) Derive bibliometric measures, 3) Perform network analysis (e.g., keyword co-occurrence), 4) Visualization of bibliometric data, 5) Interpretation of research trends, and 6) Identification of knowledge gaps [64]. Once the data is obtained, the Bibliometrix software tool [65] is utilized to derive the bibliometric measures (mentioned in Section 2.2.1). Subsequently, the network analysis, specifically the keyword co-occurrence analysis, is conducted to identify patterns and relationships among the selected keywords. The process followed in this paper to identify keywords for keyword co-occurrence analysis is illustrated in Figure 3, using VOSviewer 1.6.18 [66]. Within VOSviewer, bibliometric data in ".ris" format is selected as the data source. For the type of analysis, “Co-occurrence” is chosen, with keywords serving as the unit of analysis. The counting method is then specified as full or fractionalized counting. Subsequently, a threshold value for the minimum number of keyword occurrences is defined, yielding a list of keywords along with their respective occurrence frequencies and link strengths. This information is used to generate the network diagrams. In addition to this co-occurrence analysis, this paper also performs trend analysis using the Bibliometrix: biblioshiny tool. Here, a set of words with a chosen minimum frequency is identified in the authors' keywords, titles, and abstracts of research publications.

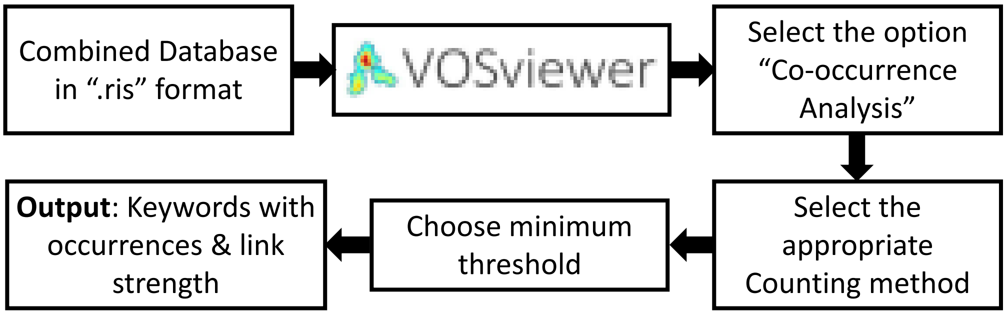

Figure 3. Procedure for Keyword Selection in Co-occurrence Analysis.

Based on the obtained data of bibliometric measures and hazard metrics, it is evident that the time series of these measures does not exhibit any linear relationship and contains a few outliers. Therefore, to analyze correlations, this paper uses Spearman correlation analysis [67]. Initially, the impact of different natural hazards is demonstrated by conducting a correlation analysis between the GRNH for various natural hazards. This analysis showcases the interdependencies among different natural hazards and underscores climate change's significance. Subsequently, correlation analyses are performed between TNP (derived from NHWC) and GRNH for all-natural hazards combined, as well as for specific hazards such as earthquakes, tsunamis, floods, windstorms, and wildfires. Furthermore, the research presents the top countries concerning RNH and their corresponding TNP values for each natural hazard, along with a combined cumulative value. Similarly, the paper highlights the top countries in terms of TNP and RNH values. From these findings, valuable insights are derived regarding highly explored natural hazards and their associated countries. In addition, countries with significant potential for resilience research are identified.

3. Results and Discussion

This section presents the results of the quantitative analysis. The results obtained from both the bibliometric and correlation approaches are discussed in the following subsections.

3.1 Results from Bibliometric Analysis

In total, 851 research publications related to power system resilience were found in Scopus and Web of Science databases between 2001 and 2022. Among these publications, original research articles account for 50.76% (432 records), conference proceedings for 41.36% (352 records), review articles for 5.29% (45 records), editorials for 0.94% (8 records), and books and book chapters for 1.65% (14 records). These publications are published in four different languages with English being the majority (97.23%) followed by Chinese (2.43%), Japanese (0.23%), and Russian (0.11%). Even though there are a few articles written in languages other than English, the titles, abstracts, and keywords of these articles were found in English in the database. Bibliometric analysis results are discussed in the following subsections.

3.1.1 Annual & Most Cited Research Publications

Figure 4 shows year-wise research publications under various document types such as original research (articles), reviews, conference proceedings, editorials, and books and book chapters from 2001 to 2022. This plot shows that from 2001 to 2006 research publications were significantly fewer with six publications. Among these, there is one review article [11] that summarizes various protection schemes that could improve power system resilience. Even though there was a rise in 2007 with five publications, the TNP until 2014 is relatively low, with year-wise publications less than ten. In 2015, there was a noticeable increase with a TNP of sixteen, and since then the trend has exponentially increased. In other words, 94.83% of publications were published between 2015 and 2022. Further, the trend of ATCpA and ATCpY for various types of publications (or document types) is shown in Figure 5 and Figure 6, respectively. These plots show that both ATCpA and ATCpY spiked in 2017, specifically corresponding to review articles. The reason for this is the significance of ATCpA and ATCpY for review articles published in 2017. In other words, considering the importance of these metrics (discussed in section 2), the review articles published in 2017 have had a significant impact and are widely recognized. To mention, only one review article was published in 2017 and has a TC of 354 (until 2022) that provides future directions regarding the use of networked microgrids for improving power system resilience [33].

Further, the 851 research publications from 2001 to 2022 have been cited 14,668 times, with an average TCpY of 3.04. Out of 851 publications, 235 publications (27.61%) were cited zero times, 378 publications (44.42%) were cited 1-10 times, 175 publications (20.56%) were cited 11-50 times, twenty-seven publications (3.17%) were cited 51-100 times, and thirty-six publications (4.23%) were cited more than 100 times. In general, there is an assumption that publications with the highest TC and TCpY reflect the quality and influence of that research work in the related field. With this assumption, the top ten most cited research publications are tabulated in Table 2 by ranking them according to TC. To mention, the journals *"Proceedings of IEEE"*, *"IEEE Transactions on Power Systems"* and *"Reliability Engineering and System Safety"* are best represented with two publications each in the top ten most cited publications.

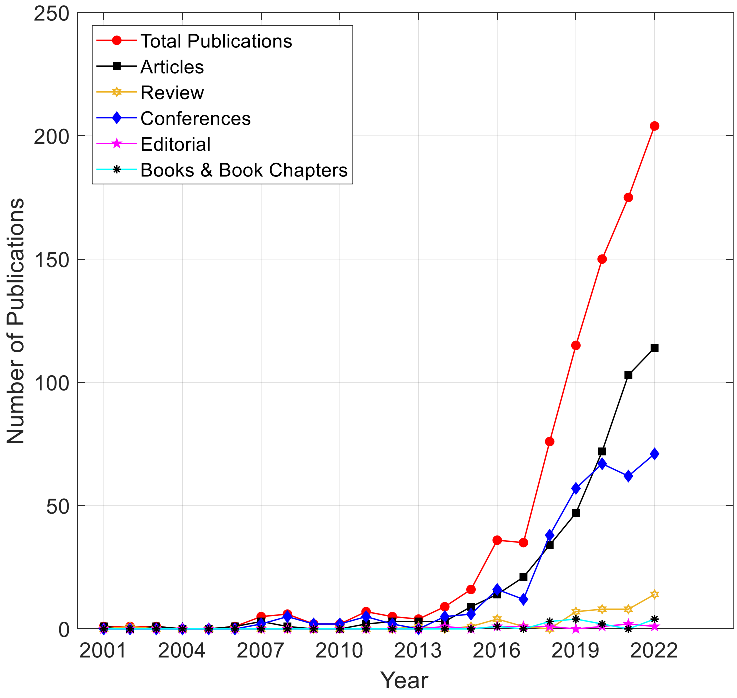

Figure 4. Annual Research Publications related to Power System Resilience from 2001-2022.

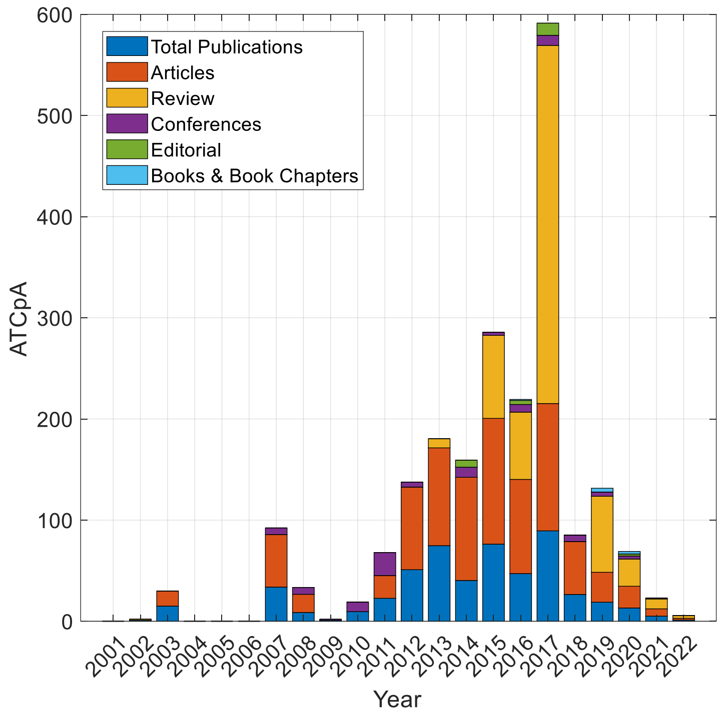

Figure 5. Average Total Citations per Article of Various Research Publication Types.

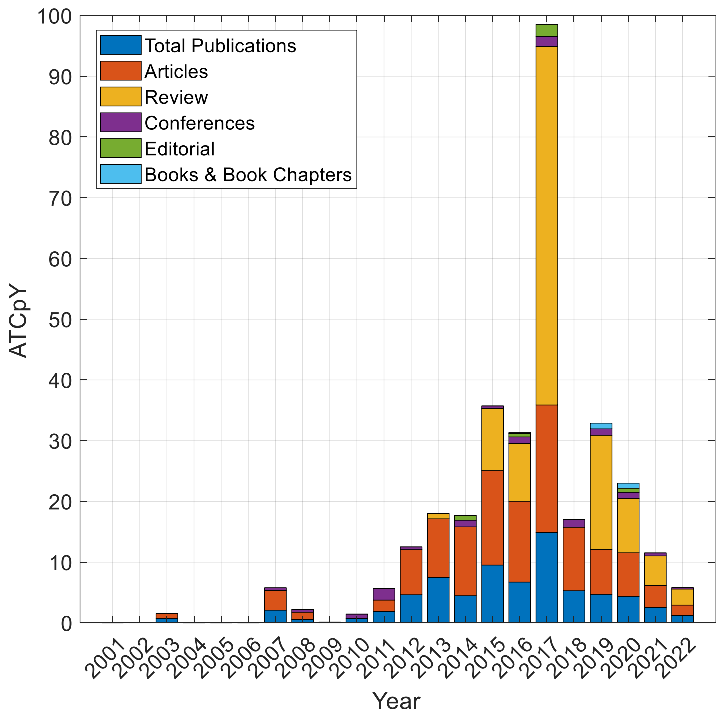

Figure 6. Average Total Citations per Year of Various Research Publication Types.

TABLE 2. TOP TEN MOST CITED PUBLICATION.

Rank	Paper Ref	Paper	Journal	Country	TC	TCpY	YP
1	[8]	The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience	IEEE Power and Energy Magazine	UK	409	45.44	2015
2	[33]	Networked Microgrids for Enhancing the Power System Resilience	Proceedings of the IEEE	USA	354	50.57	2017
3	[68]	Battling the Extreme: A Study on the Power System Resilience	Proceedings of the IEEE	China	347	49.57	2017
4	[17]	Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems	IEEE Transactions on Power Systems	UK	337	48.14	2017
5	[14]	Resiliency-Oriented Microgrid Optimal Scheduling	IEEE Transactions on Smart Grid	USA	297	29.70	2014
6	[5]	Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures	IEEE Transactions on Power Systems	UK	289	41.29	2016
7	[16]	Resilience-based network component importance measures	Reliability Engineering & System Safety	USA	281	25.55	2013
8	[20]	Modeling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events	IEEE Systems Journal	UK	276	39.43	2015
9	[69]	Enhancing Power System Resilience Through Hierarchical Outage Management in Multi-Microgrids	IEEE Transactions on Smart Grid	Iran	274	34.25	2016
10	[70]	Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis	Reliability Engineering & System Safety	China	247	27.44	2015

3.1.2 Most Productive & Cited Countries

Researchers from fifty-five different countries published their work on power system resilience from 2001 to 2022. The most productive countries are analyzed in terms of TNP and the most cited countries in terms of TC and AAC. The top fifteen most productive countries are shown in Figure 7. The United States of America (USA) has the highest TNP with 40.64%, preceded by China with 30.05%. Further, the top fifteen most cited countries are shown In Figure 8, where in terms of TC the USA has the highest with 48.40%, followed by China with 29%, while in terms of AAC, Hong Kong has the highest (80), followed by Singapore (75) and Cyprus (65). By comparing Figure 7 and Figure 8, it is evident that in both TNP and TC, the top four countries remain the same. Therefore, the USA has made a very significant contribution to power system resilience, followed by China, Iran, and the UK. However, by ranking the countries based on AAC, countries like Hong Kong, Singapore, and Cyprus have made impactful contributions to power system resilience.

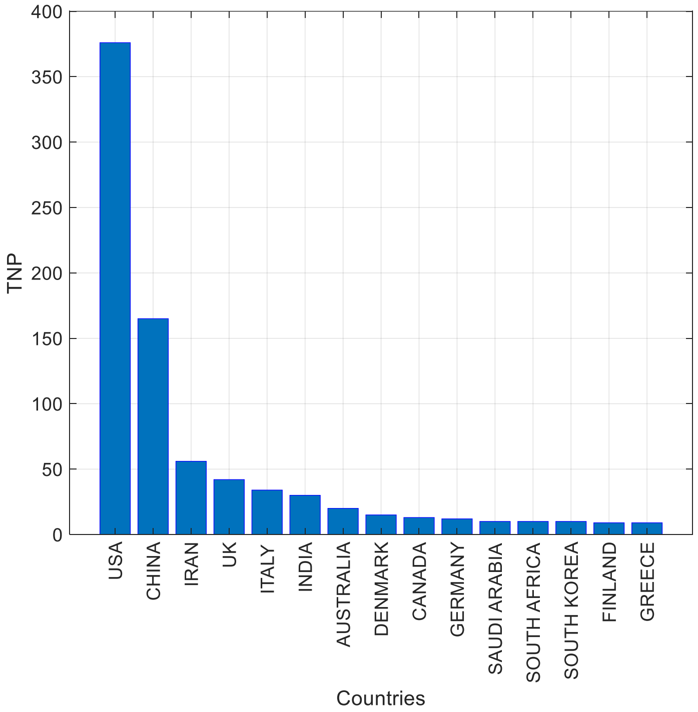

Figure 7. Top Fifteen Most Productive Countries.

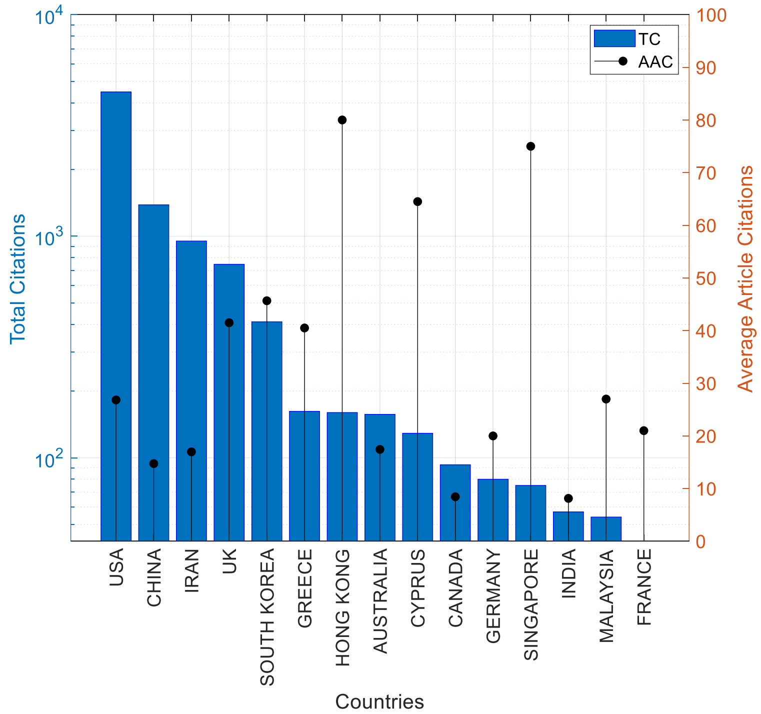

Figure 8. Top Fifteen Most Cited Countries.

3.1.3 Most Productive Institutions and Journals

There are 762 different institutions or organizations that conduct research in power system resilience. Out of these 483 institutions (63.39%) produced only one publication, 228 institutions (29.92%) produced two to five publications, thirty-three institutions (4.33%) produced six to ten publications, and eighteen institutions (2.36%) produced publications greater than ten. The top ten most productive institutions are derived based on metrics such as TC, TNP, and RII and tabulated in Table 3. It can be seen that “The University of Manchester” has the highest position in terms of TC and RII. Washington State University has the highest position in terms of TNP. When determining the most productive journals, both original research and review publications are considered. The top ten most productive journals are evaluated in terms of H-index, G-index, M-index, RII, TC, and TNP and are listed in Table 4. From this table, IEEE Transactions on Smart Grid can be ranked number one based on H-index, M-index, and TC while IEEE Transactions on Power Systems can be ranked number one based on G-index and TNP and IEEE Power and Energy Magazine can be ranked number one based on RII.

TABLE 3. TOP TEN MOST PRODUCTIVE INSTITUTIONS.

Institution	Country	TC	TNP	RII
Washington State University	USA	416	29	14.34
Xi'an Jiaotong University	China	1186	25	47.44
Illinois Institute of Technology	USA	1582	23	68.78
Sharif University of Technology	Iran	390	20	19.50
University of Utah	USA	127	20	6.35
The University of Manchester	UK	1997	19	105.11
National technical university of Athens	Greece	1155	16	72.19
Iowa State University	USA	334	15	22.27
North China Electric Power University	China	158	15	10.53
Sandia National Laboratories	USA	62	15	4.13

TABLE 4. TOP TEN MOST PRODUCTIVE JOURNALS.

Journals	H-index	G-index	M-index	TC	TNP	RII
IEEE Transactions on Smart Grid	22	40	2.2	2658	40	66.45
IEEE Transactions on Power Systems	20	41	0.952	2049	41	49.98
International Journal of Electrical Power and Energy Systems	12	22	1.714	532	26	20.46
IEEE Access	11	27	1.375	779	27	28.85
Energies	10	17	1.25	329	24	13.71
Reliability Engineering and System Safety	10	12	0.909	696	12	58.00
IEEE Systems Journal	9	13	1.286	527	13	40.54
Electric Power Systems Research	8	12	0.889	324	12	27.00
Applied Energy	7	10	1.167	576	10	57.60
IEEE Power and Energy Magazine	5	6	0.556	557	6	92.83

3.1.4 Keyword Co-occurrence Analysis

Keyword co-occurrence refers to the frequency with which two or more keywords appear together in a given dataset. These keywords encompass both indexed terms and authors' keywords, allowing them to reflect both the problem or topic of the research and the methods employed to address the research problem. For instance, the problem could be "demand-side-management", which can be addressed through various "optimization" techniques. As a result, authors might use both demand-side-management and optimization techniques in their keywords. Therefore, this type of analysis provides valuable insights into both emerging research problems and the solutions applied to address these issues.

From the research publication database, authors used 5060 keywords in 851 research publications. The procedure outlined in Figure 3 is applied to select keywords for co-occurrence analysis. While choosing the counting method that determines the weight of each co-occurrence, it is observed that there is no significant change in the set of keywords obtained for both full and fractional counting, given the available data. Therefore, this paper opts for full counting for demonstration purposes. As mentioned earlier, various forms and expressions of keywords, such as singular and plural, as well as synonyms, are unified using the thesaurus file option in VOSviewer. For example, terms like "disasters," "extreme weather events," "extreme weather," and "extreme events" are unified into a single keyword, "disasters." Through this process, the total number of different keywords is reduced to 5001 distinct keywords. Furthermore, a minimum threshold of twenty is applied to the keywords, resulting in a set of twenty-one keywords. The relationship between these keywords is represented using a network graph, as illustrated in Figure 9. In this plot, the size of the nodes is proportional to the number of occurrences and the thickness of the edges to their linking strength. Additionally, four different colors were utilized to represent four distinct clusters of keywords. In general, each cluster refers to a domain in the field of study, meaning that these keywords frequently appear together in most research publications.

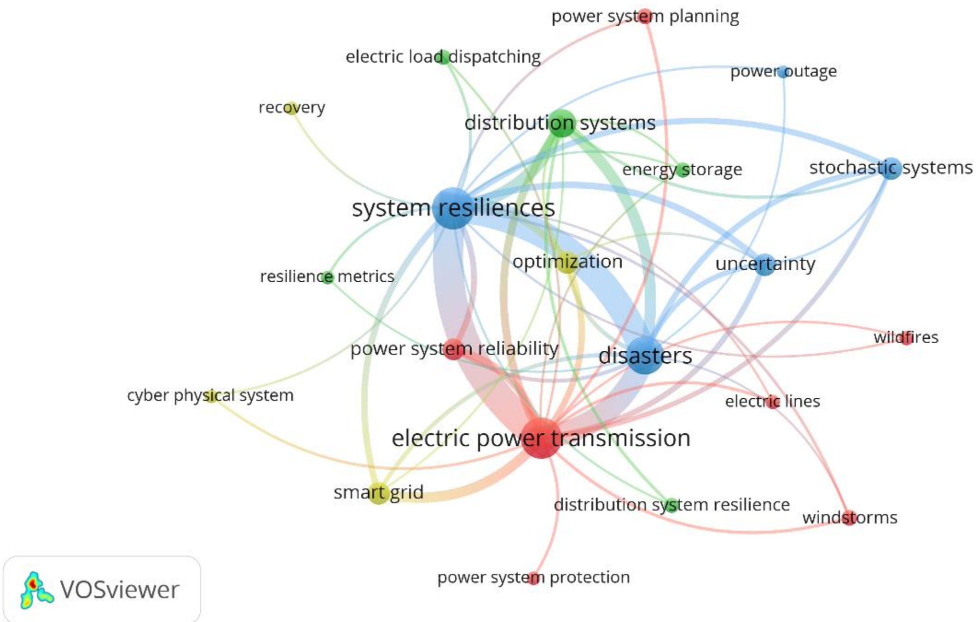

Figure 9. Keyword Co-occurrence Network of Research Publication.

The following insights are derived from Figure 9: 1) Cluster I (highlighted in red) consists of seven keywords, out of which three show a broader domain of power system resilience. It includes terms like "power system planning," "power system reliability," and "power system protection," which are all fundamental aspects of electric power systems. The presence of terms like "wildfires," "windstorms," "electric power transmission," and "electric lines" in this cluster suggests a focus on understanding and mitigating the impact of natural hazards on power systems, specifically on power transmission lines. As proof, the term “electric power transmission” has a total link strength of 943, indicating that most of the resilience studies are performed on transmission systems. Further, the link strength of “wildfires” (sixty-seven) and “windstorms” (eighty-eight) indicates that windstorms are highly studied compared to wildfires; 2) Cluster II (highlighted in green) contains five keywords that revolve around the resilience enhancement in distribution systems. The term “distribution systems” in this cluster has a total link strength of 387, indicating its significance. For instance, the terms “distribution system resilience” and “resilience metrics” indicate a focus on assessing and improving the ability of the distribution system to withstand and recover from disruptions. The terms “electric load dispatching” and “energy storage” indicate that this action is performed by optimal management of load and energy storage systems to meet the demand of the distribution system; 3) Cluster III (highlighted in blue) consists of five keywords that show a broader theme of dealing with disasters and uncertainties in power systems. The term “disasters” in this cluster has a total link strength of 788, indicating its significance. Furthermore, the terms “disasters” and “power outages” are explicit indicators of this theme, highlighting the challenges power systems face during natural hazards. Additionally, the terms “stochastic systems” and “uncertainty” have link strengths of 204 and 210, respectively, suggesting a focus on modeling random events and uncertainties using stochastic models. Moreover, the presence of “system resilience” with a link strength of 998, along with other terms in this cluster further emphasizes the importance of understanding and improving power system resilience in unpredictable situations; 4) Cluster IV (highlighted in yellow) contains four keywords that are more focused on advanced technologies and concepts related to power systems. The term “cyber-physical system” suggests a combination of physical and communicational infrastructure, specifically the threats related to cyber-attacks on physical systems. Additionally, “recovery” refers to the strategies that are developed for recovering power systems from disruptions and failures. “Smart grid” points to the application of smart technologies in power systems to enhance efficiency, and finally, “optimization” is related to the optimization of the overall performance of the power system during the event.

Emerging hotspots or concepts can be identified by using the values of occurrences and link strength, as well as by reflecting the co-occurrence of these keywords on a time scale, as illustrated in Figure 10. In general, keywords with lower occurrences but significant link strength indicate emerging hotspots. In line with this, keywords such as “cyber-physical system,” “resilience metrics,” “wildfires,” “distribution system resilience,” “recovery,” and “electric lines” have occurrences of less than twenty-five times but possess a link strength of more than sixty. Furthermore, Figure 10 reveals that keywords such as “wildfires,” “distribution system resilience,” “resilience metrics,” “power outage,” and “electric load dispatching” appear in the late 2020s. It is noticeable that “electric power transmission” appeared in the early 2019s, while “distribution system resilience” emerged in the late 2020s, indicating a clear shift in resilience research focus from transmission systems to distribution systems. Moreover, the edges linking “optimization” to “electric load dispatching,” “uncertainty,” and “distribution systems” clearly indicate the scope of optimizing power system resilience in distribution systems with novel resilience metrics. Even though a higher minimum threshold enhances the quality of the network plot, it narrows down the selection and affects the time scale. Therefore, further analysis is conducted to refine trending research topics (see next subsection).

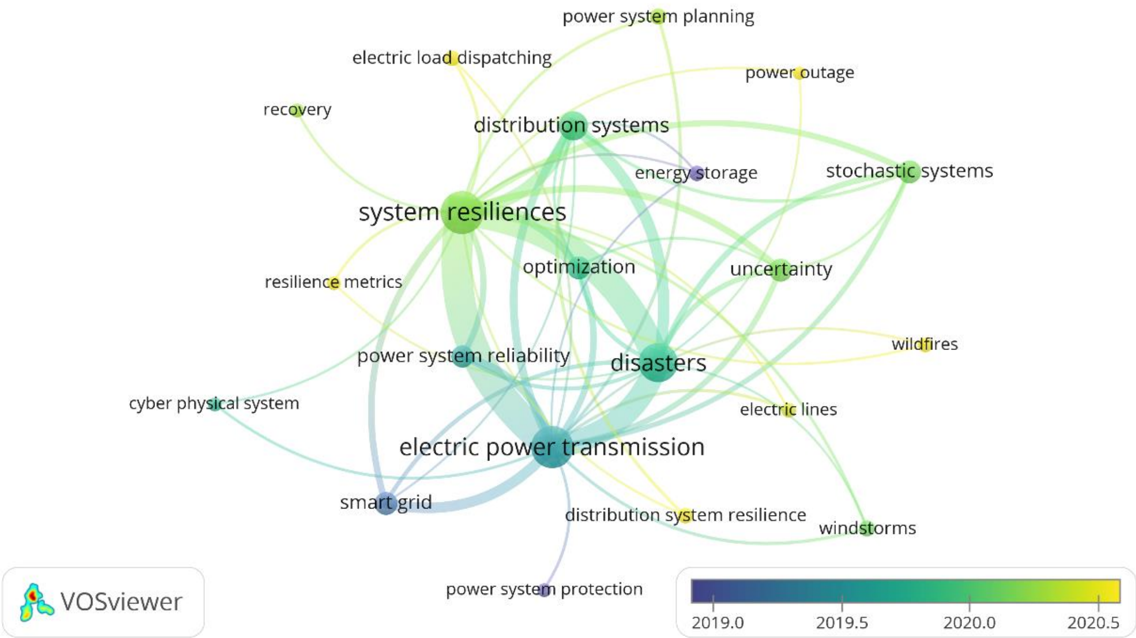

Figure. 10 Keyword Co-occurrence Network on Time Scale.

3.1.5 Research Trend Analysis

Research trend analysis is performed using the number of occurrences of authors’ keywords, trigram words in titles, and bigram words in abstracts. To derive meaningful outcomes from trend analysis, we chose a trigram for the title and a bigram for the abstract. This analysis is carried out by considering a minimum word frequency of five and selecting the top two words in any particular year. Figure 11, Figure 12, and Figure 13 show trending words from the author's keywords, abstracts, and titles. As mentioned in Section 3.1.4, the authors’ keywords reflect not only the research problem or topic but also the methods employed to address it. For example, in Figure 11, it can be seen that “power system resilience,” the research topic, and “optimization,” the research method, appear together from 2019 in the authors’ keywords. This indicates that power system resilience is improved through optimization techniques. Similarly, this pattern can also be observed in repeated words within research publications abstracts. For instance, in Figure 12, it can be seen that “resilience-based planning”, the research topic, and “genetic algorithm”, the research method appeared together between 2016 and 2018. Therefore, in addition to analyzing the authors’ keywords, considering the bigram words (word pairs) in the abstracts can also provide valuable insights into both the research problem and the employed methods. However, it is important to note that this level of information may not be as visible in the title words, as titles tend to focus on the subject or topic of the research.

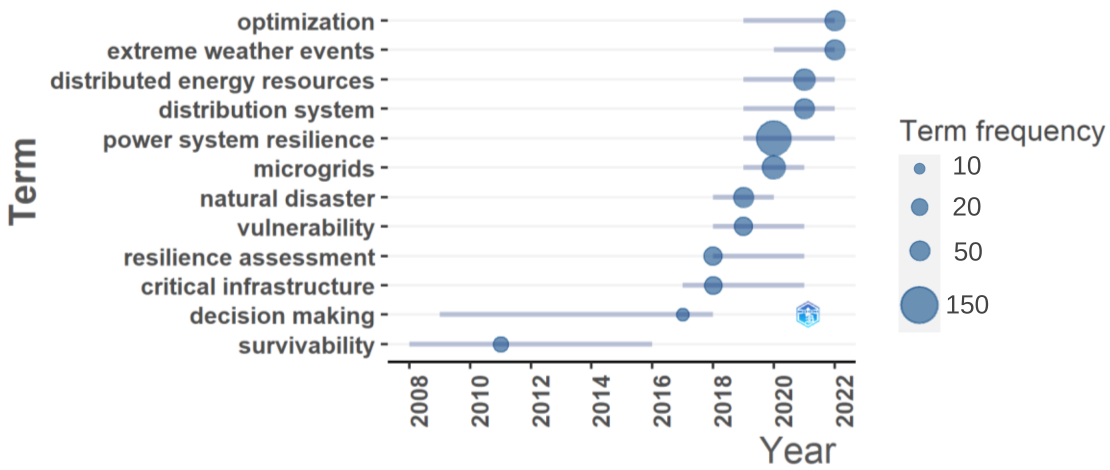

Figure 11. Authors' Keywords from Trending Analysis.

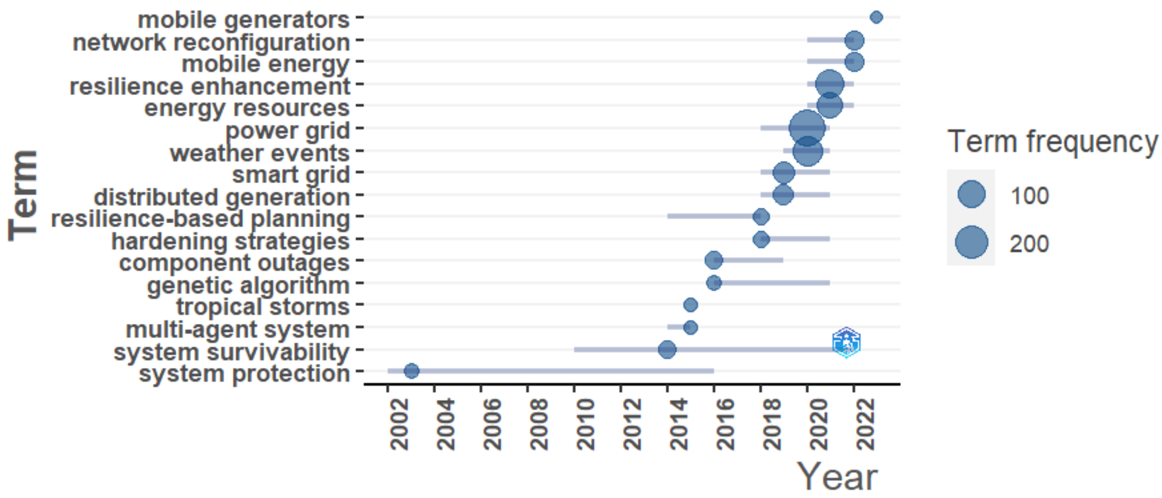

Figure 12. Bigram words in Abstracts from Trending Analysis.

The trends in authors’ keywords depicted in Figure 11 reveal several interesting observations. The term “survivability” began appearing around 2008 and remained a prominent part of authors’ keywords until 2016. Following this, “decision-making” became a significant keyword from 2009 to 2018. Starting from 2018, it can be observed that keywords such as “critical infrastructure,” “resilience assessment,” “vulnerability,” and “natural disaster” have emerged. This indicates a growing popularity of resilience, with many research publications focusing on mitigating critical infrastructure vulnerability against natural disasters to enhance overall system resilience. Additionally, keywords that appeared in 2019, such as “microgrids,” “optimization,” “distributed energy resources,” and “distribution system” suggest an extension of the concept of resilience towards the distribution system. This is achieved by implementing microgrids with optimized distributed energy resources. Moreover, the term “natural disasters” has changed its form to “extreme weather events” since 2019 reflecting a changing focus in resilience research, where models and strategies are being developed to address the impact of extreme weather events on power systems.

Furthermore, the bigram words in the abstract, as shown in Figure 12, reveal various insights and support a few observations seen in the trend of authors’ keywords. The term “system protection” was observed from 2002 and remained until 2016, followed by “system survivability” from 2010. The terms “hardening strategies,” “distributed generation,” “power grid,” and “genetic algorithm” appeared together from the year 2018. This suggests that the power grid's resilience is improved by optimal allocation of distributed generation and implementing line hardening using genetic algorithms. In practice, this is achieved by minimizing either the cost of chosen resources or the system performance measure (e.g., energy not served) during the event. Furthermore, terms such as “mobile energy,” “mobile generator,” “network reconfiguration,” “resilience enhancement,” and “energy resources” began to appear from 2020. This indicates that resilience enhancement methods now involve energy resources, with a focus on mobile energy storage or mobile generation, along with network reconfiguration to improve system resilience. Implementing this approach enhances operational resilience. Similarly, the trigram words of the title, as shown in Figure 13, indicate that the research subject of “power system survivability” in terms of resilience appeared from 2008 to 2012. However, at the beginning of 2020, the research focus shifted more toward “extreme weather events” and “power distribution systems”. Furthermore, from the late 2020s, terms such as “distribution system resilience” and “distribution system restoration” appeared alongside “extreme weather events”. This trend aligns with the observations in the authors’ keywords, where research on resilience has shifted toward the distribution system since 2020.

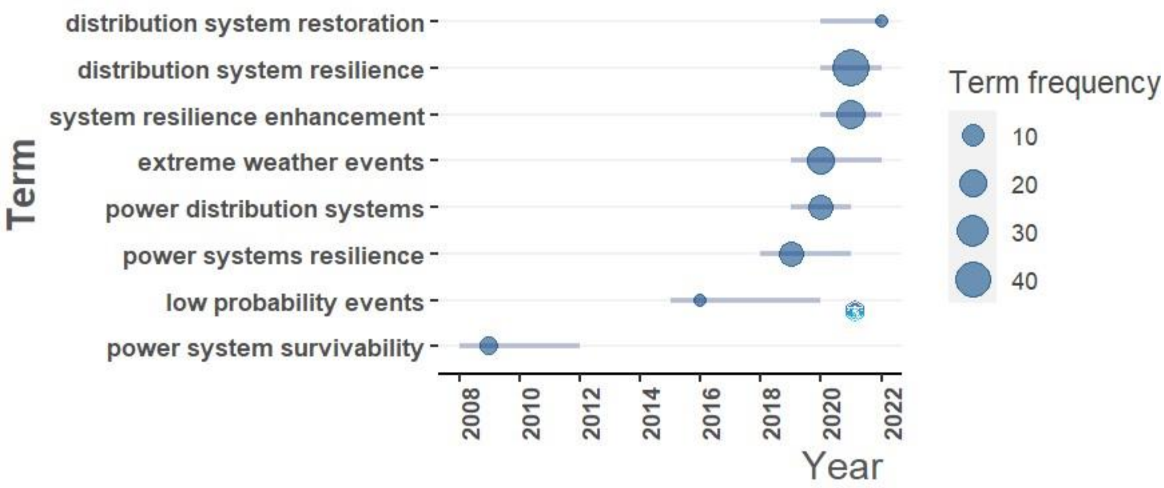

Figure 13. Trigram words in Titles from Trending Analysis.

Overall, from the trend analysis, initial research on power system resilience (until 2015) centered on protection schemes, decision-making tools, and system survivability techniques. Towards the end of 2015 or the beginning of 2016, research started exploring the survivability of networks against tropical storms. Between 2016 and 2019, most resilience enhancement methodologies focused on the power transmission system. From 2020, many research work were focused on developing methodologies that enhance distribution system resilience.

To better understand this transition and identify the evolution of authors' keywords in the field of power system resilience, a thematic evolution analysis of these keywords is conducted using the Bibliometrix software tool. This analysis is performed by slicing the time into three segments based on year-wise TNP (TNPy) defined by A: 2001 – 2017 ($TNPy \leq 50$), B: 2018 – 2020 ($51 \leq TNPy \leq 150$), and C: 2021 – 2022 ($TNPy > 150$). Furthermore, the minimum keyword frequency considered in the analysis is 10. This approach allows for a comprehensive examination of the changes and trends in the keywords used by authors in power system resilience research over time. The authors' keywords obtained in segment 'A', such as critical infrastructure, distributed energy resources, microgrids, power grid resilience, power system survivability, power system stability, risk, restoration, and natural disasters, represent resilience research up to 2017. Furthermore, the evolution of these keywords over three distinct time periods is visualized using the Sankey diagram presented in Figure 14.

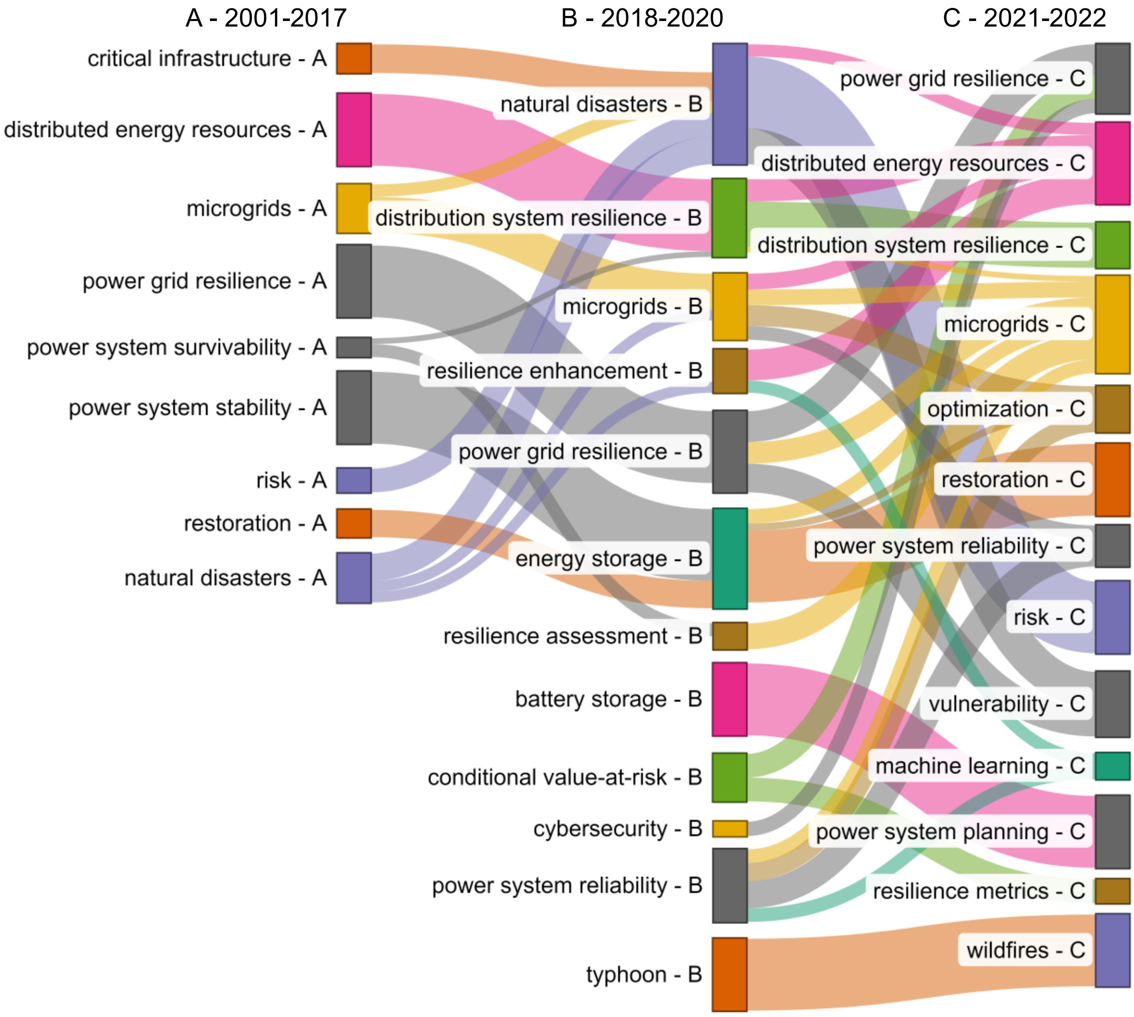

Figure 14. Thematic Evolution of Authors' Keywords from 2001 to 2022.

Notable insights from keywords linking segment ‘A’ to segment ‘B’ are as follows: 1) In the segment ‘A’, the keyword “critical infrastructure” is associated with “natural disasters” during segment ‘B’. This indicates that from 2018 to 2020, research efforts have focused on exploring critical infrastructure vulnerabilities concerning natural disasters. This shift in association suggests a growing interest in understanding how critical infrastructure can withstand and recover from natural hazards. 2) The connection between “distributed energy resources” in segment ‘A’ and “distribution system resilience” in segment ‘B’ highlights the research focus on exploring how distributed energy resources can enhance distribution systems’ resilience. This suggests that during 2018-2020, there have been efforts to investigate the role of distributed energy resources in improving the overall resilience of distribution networks. 3) In the segment ‘A’, research on “microgrids” is linked to “natural hazards” in segment ‘B’. This implies that researchers have been studying microgrids' potential as resilient solutions to natural hazards. The association indicates a growing interest in understanding how microgrids can contribute to power systems’ resilience in the face of natural disasters. 4) The linkage between “restoration” in segment

‘A’ and “energy storage” in segment ‘B’ reveals that the restoration process after natural disasters has been improved by utilizing energy storage systems. This connection suggests that during 2018-2020, there has been a focus on integrating energy storage technologies to enhance power system restoration and recovery following natural hazards.

The Sankey diagram reveals an additional set of keywords from segment ‘B’ connected to segment ‘C’. For instance, the linkage between “battery storage” and “power system planning” indicates that the optimal allocation of battery storage systems in power grids is conducted during this period as part of power system planning. Notably, the inclusion of “conditional value-at-risk” (CVaR) with “resilience metrics” and “power grid resilience” suggests that researchers have introduced a novel risk-based metric (i.e., CVaR) to quantify power grid resilience during this time.

Furthermore, it is evident from the diagram that investigations into cybersecurity-related threats to the power system are ongoing in the context of power grid resilience. Additionally, the connection between “resilience enhancement” and “power system reliability” in segment ‘B’, and “machine learning” in segment ‘C’ indicates an extended application of machine learning to improve both power system reliability and resilience. Moreover, the emphasis on research related to wildfires in segment ‘C’ highlights the growing attention given to understanding and mitigating their impact on critical infrastructure, especially when compared to typhoons. Furthermore, the links between “resilience enhancement” in segment ‘B’ and “distributed energy resources” in segment ‘C’, and “distribution system resilience” in segment ‘B’ and “distributed energy resources” in the segment ‘C’, indicate that research on resilience enhancement in distribution systems initiated during segment ‘B’ is continuing into segment ‘C’.

These insights demonstrate a progression in research focus and ongoing efforts to enhance power system resilience, especially with the introduction of new metrics and the application of machine learning techniques. The increased attention to wildfires reflects contemporary challenges and priorities in safeguarding critical infrastructure against natural disasters. Additionally, the continuity of research on distribution system resilience enhancement signifies the persistence of efforts to strengthen distribution networks' resilience with the incorporation of distributed energy resources.

3.2 Results from Correlation Analysis

Bibliometric analysis points us in the direction of research hotspots or topics on which future research about power system resilience needs to be conducted. Nevertheless, determining the correlation between bibliometric measures and the natural hazard risk in different countries will yield valuable insights. This includes natural hazards that attract prime focus, lesser explored natural hazards, countries that carry out natural hazard-focused resilience research (also called event-specific research), and countries that need more attention. As mentioned in Section 2.2.1, the correlation of global risk from various natural hazards is briefly demonstrated to showcase climate change's criticality. Furthermore, the outcomes of different correlation analyses between TNP (derived from NHWC), GRNH, and RNH for the combined risk of natural hazards and individual hazards are presented. In this analysis, since there were very few research publications in the initial period, all correlation analyses were performed for the last decade, i.e., from 2013 to 2022.

3.2.1 Correlation between TNP and GRNH

The Spearman correlation coefficient, denoted as ρ, is used to analyze the GRNH of different natural hazard types, as depicted in Figure 15a. It is worth noting that since the GRNH values are in different ranges, normalization is applied using min-max normalization (referred to as GRNH′) to derive this correlation. From the plot, it is observed that $GRNH_{EQ}$ exhibits a strong positive correlation with $GRNH_{TS}$ and $GRNH_{FL}$ with coefficients of 0.75 and 0.79, respectively. This finding suggests that areas with higher earthquake risk are also likely to have higher tsunami and flood risks. It is essential to emphasize that this statement holds particular relevance for countries with coastal regions vulnerable to earthquakes and tsunamis, such as Japan. Additionally, tsunamis cause significant floods globally, and this is reflected in the strong positive correlation of 0.95, indicating that regions prone to tsunamis are also at risk of floods. In the case of $GRNH_{WS}$ and $GRNH_{WF}$, weaker correlations are observed with other variables, with coefficients ranging from 0.06 to 0.44. This suggests that the risk of windstorms and wildfires might not be as strongly related to the risk of earthquakes, tsunamis, and floods. Overall, Figure 15a indicates that there are some shared patterns and associations between different natural hazards in terms of global risk. To gain insights into how the research community studies the impact of these natural hazards on power systems, a correlation between the TNP (derived from bibliometric measures) and the combined normalized GRNH (i.e., the sum of normalized GRNH values for all-natural hazards) is performed and shown in Figure 15b. It can be observed that TNP exhibits a strong positive correlation with GRNH′, with a coefficient of 0.84. This finding demonstrates that many researchers recognize the importance of power system resilience studies and have conducted various investigations concerning the impacts of different natural hazards on power systems. This increased interest in resilience research is driven by the escalating impact of natural hazards on power infrastructure. However, while this analysis provides an overall view of the rising interest in resilience research due to the amplified impact of natural hazards, it is essential to delve deeper into individual hazard studies, which are discussed further.

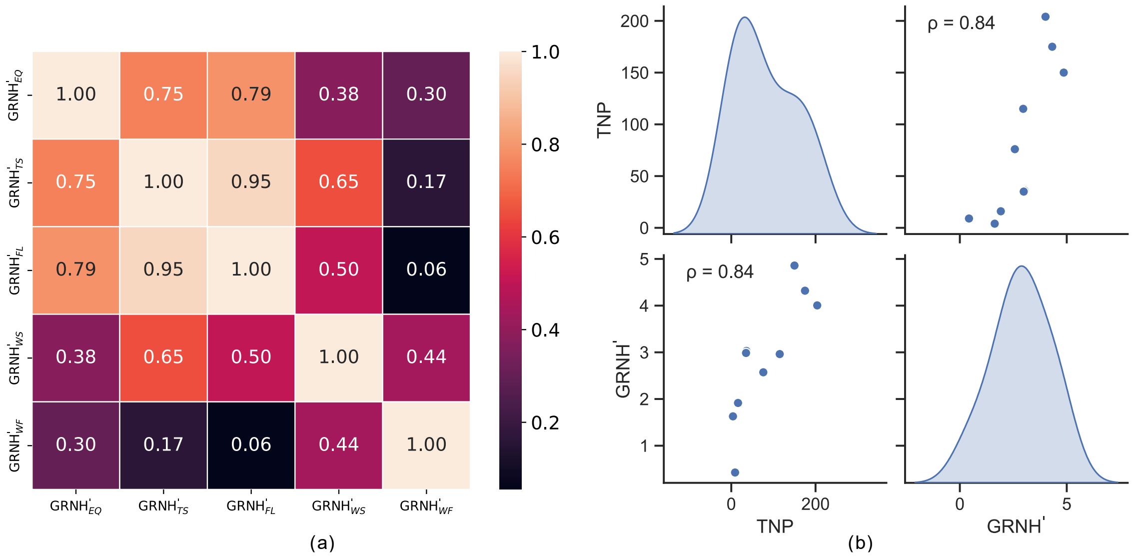

Figure 15. Spearman Correlation Coefficient (a) GRNH' of Different Natural Hazards (b) TNP vs GRNH'.

The correlation analysis between TNP (derived from NHWC) for each natural hazard, such as earthquakes, floods, windstorms, and wildfires, and their corresponding GRNH′ is presented in Figure 16. It is important to note that there was no TNP related to tsunamis in power system resilience, hence its absence in Figure 16. From Figure 16a, it is evident that there is a strong positive correlation between TNP_{EQ} and $GRNH'_{EQ}$, with a coefficient of 0.74. A similar trend is also observed between TNP_{FL} and $GRNH'_{FL}$. These results indicate that as the risks due to earthquake and flood increases, there is a growing interest in understanding and addressing their impact on power system resilience. Despite windstorms having a significantly higher number of TNP than other natural hazards (which will be discussed further), the correlation coefficient between TNP_{WS} and $GRNH'_{WS}$ is 0.57. This indicates that researchers have indeed invested considerable effort in comprehending and assessing windstorm risk. However, the impact of this research effort may not be as visible in $GRNH'_{WS}$. The possible reason for this could be combining the research outcomes of the world related to windstorms and the global risk of windstorms. Alternatively, it could imply that methodologies for windstorm resilience are well-developed, but practical implementation is yet to catch up. In the case of wildfires, the correlation between TNP and GRNH′ exhibits a very weak correlation with a coefficient of 0.14. This suggests that there is a pressing need for increased focus and research on wildfires and their potential impact on power system resilience. The current level of attention to wildfires may not adequately address the potential risks posed to power infrastructure by these events.

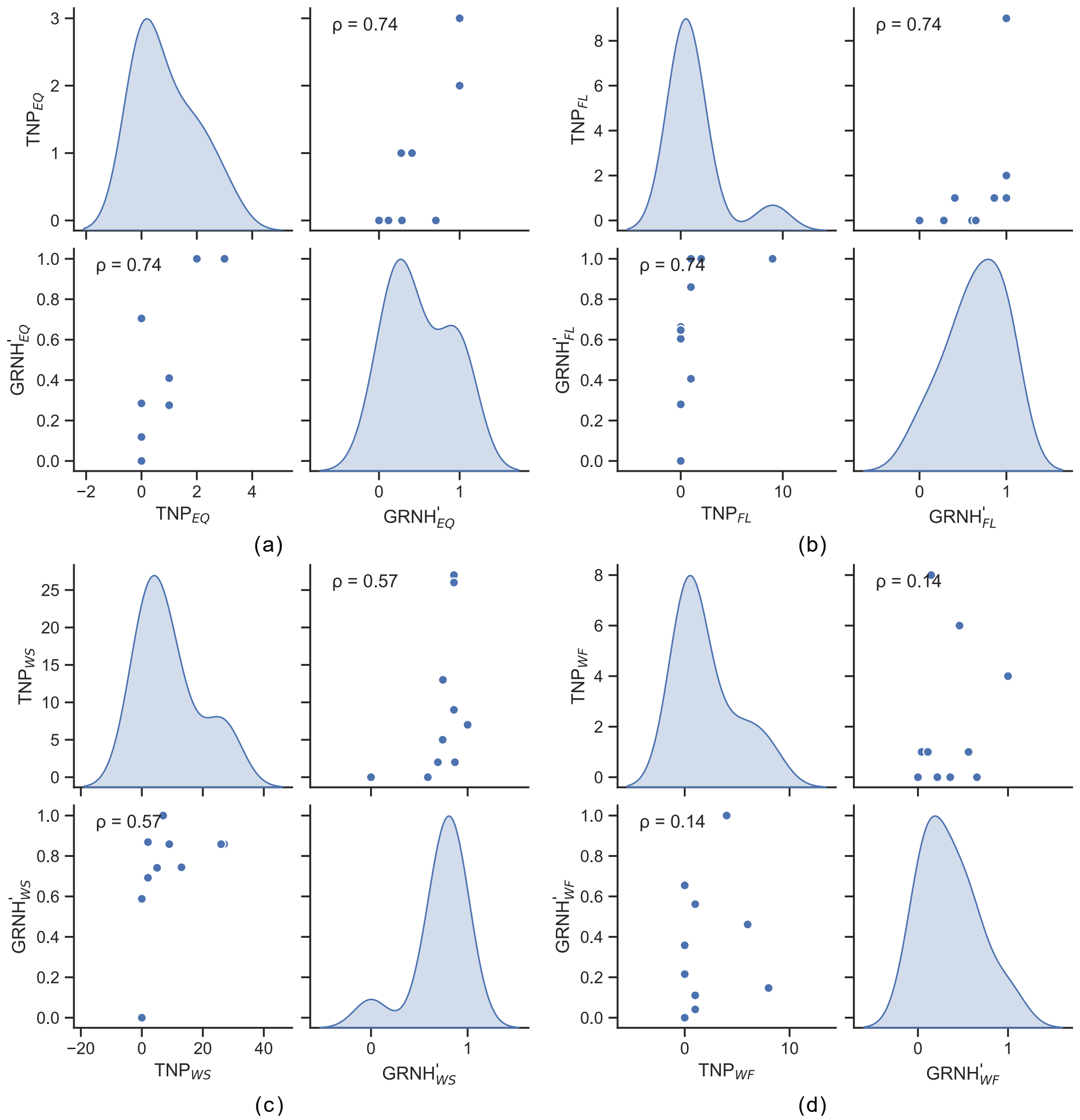

Figure 16. Correlation between TNP and GRNH′ for (a) Earthquakes (b) Floods (c) Windstorms (d) Wildfires.

3.2.2 Correlation between TNP and RNH focused on Top Countries

The correlation analysis presented in the previous subsection provides a worldwide overview. To gain insights into the prioritization of research on specific and less explored natural hazards by different countries, it is essential to correlate the TNP and RNH. This paper correlates the top ten countries based on RNH and TNP. The analysis considers both total RNH (by adding RNH values for different natural hazards) and focuses on individual natural hazards. The top countries are determined based on their RNH (both total RNH and event-specific RNH) and TNP (both total TNP derived from NHWC and event-specific TNP). To ensure rationality, this study excludes countries classified under low-income and small island developing states by the United Nations in the World Economic Situation and Prospects report [71]. The relationship between event-specific

TNP, derived from NHWC, and total RNH for the top ten countries with high total RNH is depicted in Figure 17. This plot reveals that the Philippines has the highest total RNH, exceeding 300, followed by China, Japan, and the USA. Surprisingly, there is no event-specific research related to power system resilience from the Philippines, and a similar pattern is observed for other countries like Japan, Indonesia, Mexico, and Australia. However, this contradicts Figure 7, where Australia ranks among the top fifteen most cited countries in power system resilience research. This is because Figure 7 includes all publications on power system resilience, while the correlation analysis in this section considers only event-specific TNP publications. Moreover, Figure 17 highlights that countries like China and the USA, facing high risks from natural hazards, perform well in terms of event-specific resilience research, with the USA leading, followed by China. India, also among the top ten high-risk countries, has initiated research efforts.

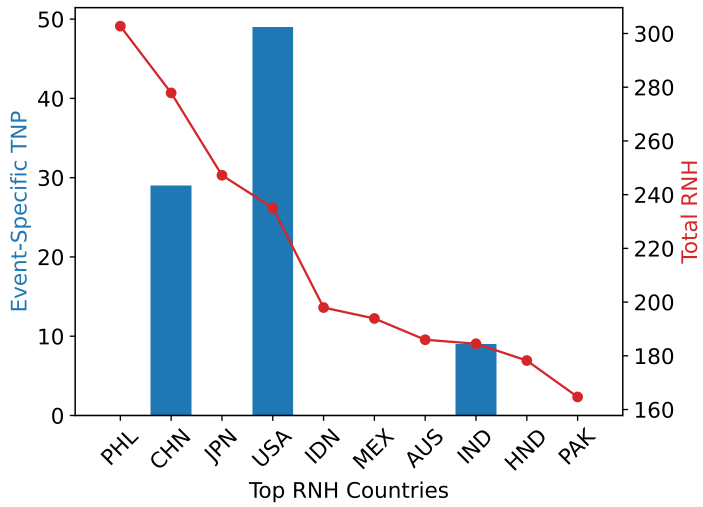

Figure 17. Relation between Event-Specific TNP and Total RNH for Top Ten High RNH Countries.

Furthermore, Figure 18 presents an analysis of the relationship between event-specific TNP and RNH for distinct natural hazards, including earthquakes, floods, windstorms, and wildfires. The analysis focuses on the top ten countries with high RNH for each of these hazards. As mentioned in Section 3.2.1, the absence of TNP related to tsunamis in power system resilience is reflected in Figure 18. From Figure 18a, it is apparent that the Philippines exhibits the highest RNH_{EQ}, approximately eighty, followed by China and Guatemala. Notably, the USA holds the 8^{th} position, displaying an RNH_{EQ} slightly higher than sixty. These top ten countries with elevated earthquake risk have only China and the USA engaged in research pertaining to earthquake impact on power systems. This observation underscores the potential for further research initiatives in other high-risk earthquake regions, such as the Philippines and Guatemala, to enhance power systems' resilience against seismic events. Examining Figure 18b, Vietnam emerges with the highest RNH_{FL}, surpassing seventy-five, followed by China and the Philippines. Within this context, research endeavors in power system resilience against floods have been more pronounced in China, India, and the USA, with the USA leading the efforts, followed closely by India and China. These findings indicate that countries experiencing heightened flood risk have demonstrated significant research interest in fortifying power system resilience against flooding. Nevertheless, Vietnam and the Philippines have untapped potential to intensify their research efforts in this domain, given their vulnerability to flooding. Figure 18c reveals that the Philippines recorded the highest RNH_{WS}, exceeding eighty, for windstorms, followed by China, Japan, and the USA. In this category, both China and the USA dominate power system resilience research addressing windstorm hazards. Intriguingly, despite occupying the top position in windstorm risk, the Philippines has not exhibited proportional research output in windstorm resilience. This disparity highlights the necessity for increased research efforts in the Philippines to address windstorm impact on power systems effectively. Regarding wildfires, Figure 18d employs a normalized wildfire risk (RNH_{WF}), with values ranging from 0 to 1, wherein 1 represents the highest risk. Angola emerges with the highest RNH_{WF}, followed by Mexico and India. While the USA ranks 7^{th}, it is the only one among the top ten countries with high wildfire risk that focuses on wildfire resilience research.

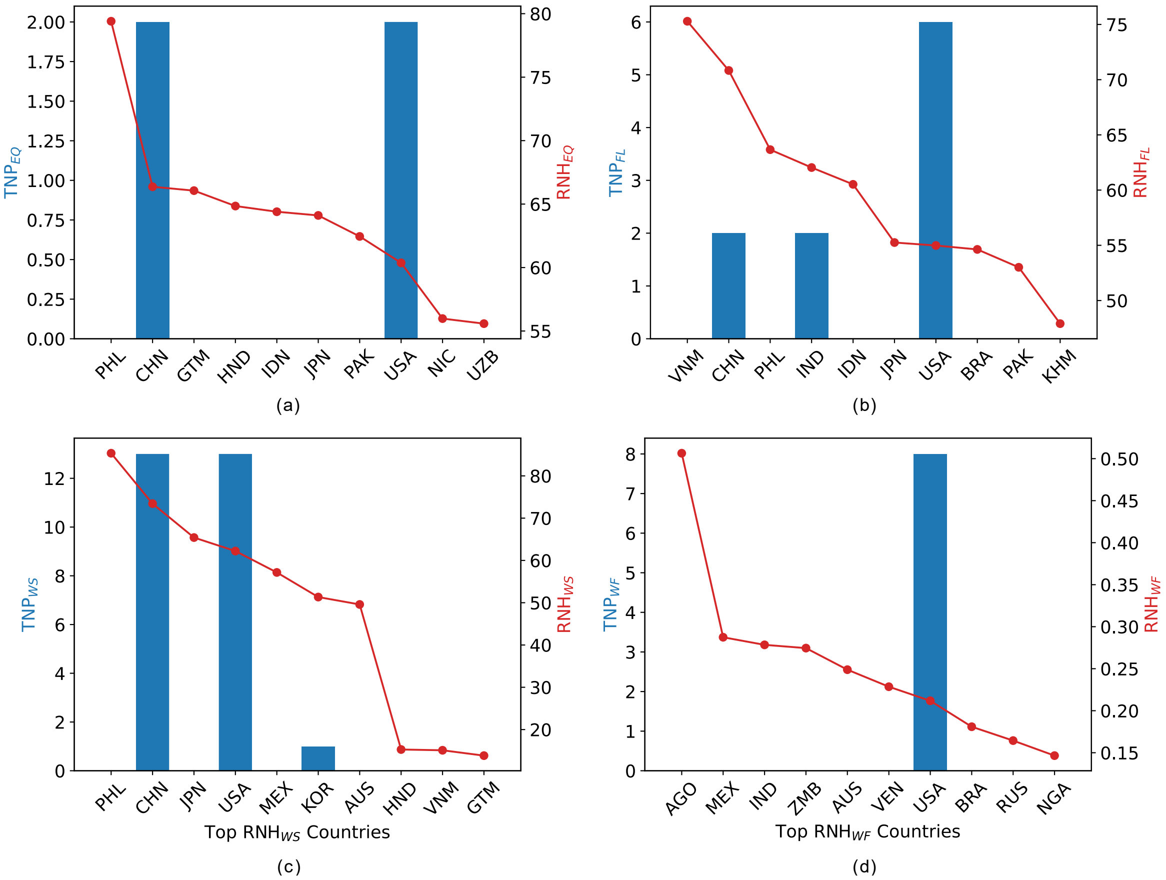

Figure 18. Relation between TNP and RNH for Top Ten RNH Countries related to (a) Earthquakes (b) Floods (c) Windstorms (d) Wildfires.

To understand the top countries that perform research in power system resilience and investigate their risk levels to different natural hazards, the relationship between their event-specific TNP and RNH is analyzed. Similar to the discussions presented related to top countries based on RNH, initially the countries with top total event-specific TNP are presented, and later, TNP specifically for each natural hazard is examined. Figure 19 illustrates the top ten countries based on event-specific TNP and their corresponding total RNH. The plot reveals that the USA possesses the highest number of event-specific TNP, nearing fifty, followed by China, Iran, and the UK (referred to as GBR). Additionally, based on the total RNH of these countries, China holds the highest position, followed by the USA and India. Although China, India, Chile, and Greece have made significant contributions to power system resilience research, comparing the proportions of TNP and total RNH indicates the need for increased focus. Conversely, Cyprus and Finland contribute to resilience research, even with a less proportionate total RNH. This highlights their dedication to addressing power system resilience, regardless of risk levels.

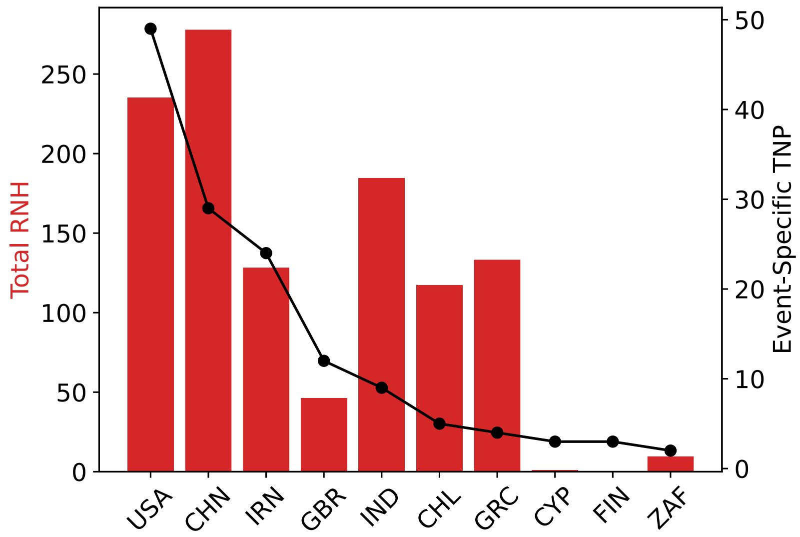

Figure 19. Relation between Event-Specific TNP and Total RNH for Top Ten High TNP Countries.

Furthermore, Figure 20 presents an analysis of the relationship between event-specific TNP and RNH for distinct natural hazards, including earthquakes, floods, windstorms, and wildfires. The analysis focuses on the top ten countries with high event-specific TNP for each of these hazards. As mentioned earlier, TNP related to tsunamis in power system resilience is not considered in Figure 20. Notably, the analysis reveals that only six countries have conducted research on earthquake and wildfire resilience in power systems. Therefore, Figures 20a and 20d represent only these six countries on the top ten list. In Figure 20a, it is evident that India has the highest TNP_{EQ} of three, followed by the USA, Iran, and China, all with equal TNP_{EQ} values of two. Despite significant research outcomes related to earthquakes, a comparison with the corresponding RNH_{EQ} indicates the need for all these countries to increase their focus on earthquake-related resilience research. Figure 20b shows that the USA has the highest number of TNP_{FL} with six, followed by the UK, India, and China. Comparing the risk levels of floods among these top countries, it becomes apparent that China faces the highest risk, followed by India and the USA. This relationship underscores the potential for all these high flood-risk countries to improve and advance their research efforts on flood resilience. Figure 20c shows the USA and China have the highest number of TNP_{WS} with twelve, followed by Iran and the UK. However, in terms of RNH_{WS} among these countries, China exhibits the highest risk level for windstorms, followed by the USA, South Korea, and India. Although South Korea has made some contributions considering its RNH_{WS}, there is huge potential for increased focus on addressing windstorm impact on power systems more effectively. Conversely, Iran ranks 3rd in terms of TNP_{WS}, despite not facing high RNH_{WS}. Finally, Figure 20d indicates that the USA has the highest TNP_{WF} with eight, followed by the UK with two. In the context of RNH_{WF} among these countries, the USA faces the highest risk, followed by China. Overall, these findings suggest that the USA and China are at the forefront of power system resilience research, dedicating considerable attention to addressing the challenges posed by various natural hazards.

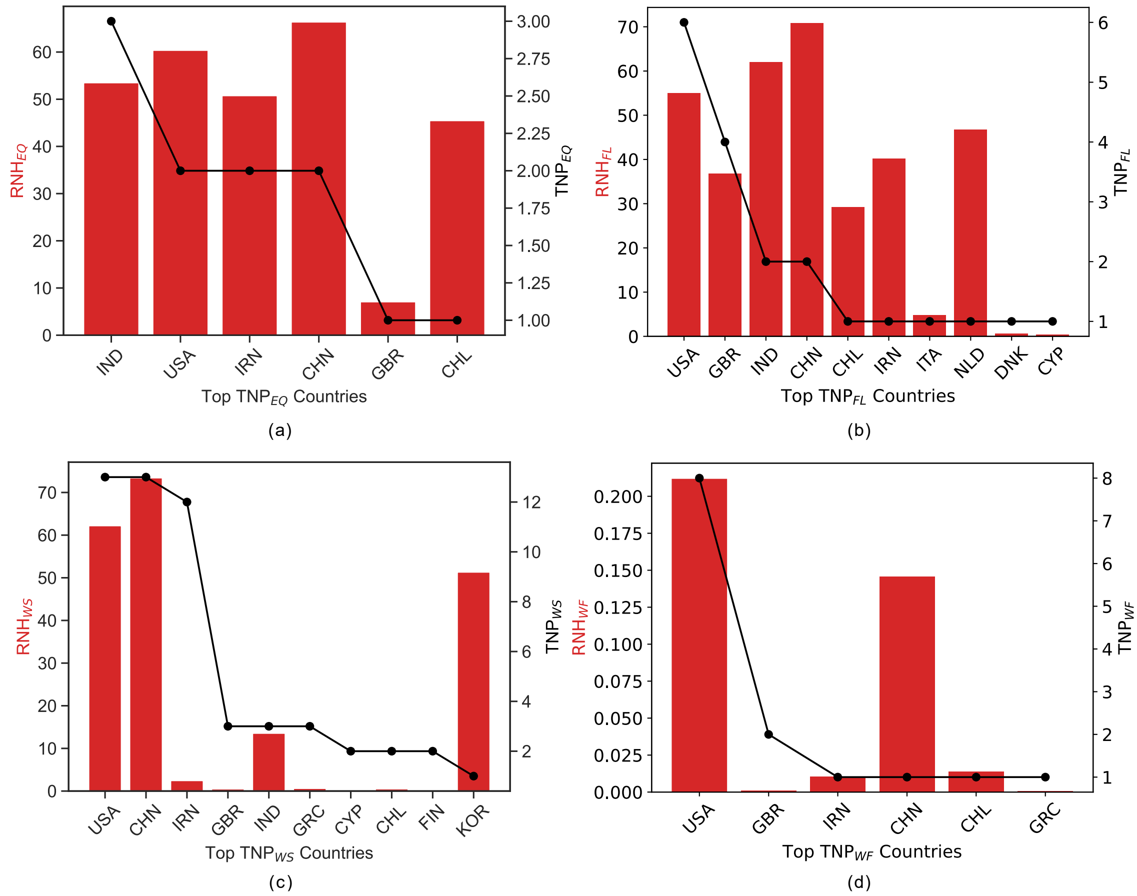

Figure 20. Relation between TNP and RNH for Top TNP countries related to (a) Earthquakes (b) Floods (c) Windstorms (d) Wildfires.

4. Conclusion

This paper proposes a methodology for quantitative analysis of research publications that combines bibliometric and correlation methods to derive insights into the field of power system resilience. The bibliometric analysis is used to identify the most productive elements, such as leading countries, journals, and institutions. Additionally, the study introduces novel hazard metrics, namely RNH, GRNH, and NHWC-driven TNP, to assess event-specific research into power system resilience. Given that research into power system resilience is driven by hazards, the integration of bibliometric and correlation analyses between bibliometric measures and hazard metrics yields valuable insights. These insights include the identification of the most explored and lesser-explored natural hazards, countries actively conducting event-specific resilience research, and countries that require more attention in this field. The findings of this study can be summarized as follows:

- The bibliometric measures, such as TNP and TC, indicate that the USA, China, Iran, and the UK are at the forefront of research, while the bibliometric measure AAC shows that Hong Kong, Singapore, and Cyprus are leading in this domain.
- Keyword co-occurrence analysis with network plots reveals a shift in research focus from electric power transmission systems to distribution systems, particularly concerning enhancing distribution system resilience. Additionally, there is increased attention to the impact of wildfires on power systems.
- Trend analysis using Sankey diagrams and other plots related to keywords, titles, and abstracts indicates battery storage and mobile generators are becoming popular in improving operational resilience. Moreover, resilience metrics such as CVaR are being applied to power system resilience, and topics like cybersecurity are gaining relevance, especially in the context of cyber-physical systems.
- The correlation analysis between TNP from NHWC and GRNH reveals that resilience research is scarcely related to earthquakes and floods. This scarcity can be attributed to the complexity involved in developing integrated hazard models for earthquakes and floods within the resilience frameworks. As for wildfires, the methodologies have primarily been developed by the USA, and there is a need to adapt them or develop new models relevant to other countries. Moreover, robust methodologies for dealing with windstorms have already been developed but are yet to be put into practice.
- Further correlation analysis between TNP from NHWC and total RNH (i.e., across all-natural hazards) indicates that high-risk countries, such as the USA and China, are making significant progress in resilience. India and South Korea also show promising advancements. Notably, resilience research is more visible in developed countries, while it is in its early stages in some developing nations. Interestingly, certain more developed countries contribute significantly to resilience research despite their low-risk levels, while this contribution is negligible in many developing and less developed countries.

While this study provides intriguing insights into power system resilience research, it does have certain limitations. Some keywords that fall below the threshold value in the keyword co-occurrence analysis seem to exert weak influence. However, this could be attributed to their weak influence or the recent introduction to the field of study. In future research, developing a specific metric that considers keywords and their year of appearance would be advantageous. Keywords from both the earliest and latest years should be treated differently. In other words, keywords from the earliest year should be handled similarly to this study, while the most recent keywords should be included in the analysis, unaffected by the threshold value.

Credit Author Statement

Balaji. V. Venkatasubramanian: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, and Visualization. **Mathaios Panteli:** Conceptualization, Methodology, Software, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, and Funding acquisition.

Acknowledgements

This work was funded by the European Union under the H2020 program through the EUniversal Project (Grant agreement ID: 864334). It was also partially funded by the Horizon Europe program through the projects “Reliability, Resilience and Defense Technology for the Grid” (R2D2) (Grant agreement ID: 101075714), “HVDC-based Grid Architectures for Reliable and Resilient WideSpread Hybrid AC/DC Transmission Systems” (HVDC-WISE) (Grant agreement ID: 101075424) and “Climate-aware Resilience for Sustainable Critical and interdependent Infrastructure Systems enhanced by emerging Digital Technologies” (ReCharged) (Grant agreement ID: 101086413).

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