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Review article

Systematic evaluation and review of Germany renewable energy research: A bibliometric study from 2008 to 2023

Haiyang He [a], Huazhong Tu [a,d,*], Hongli Zhang [a,**], Shenghong Luo [c,d], Zheng Ma [b], Xinmiao Yang [a], Yumeng Li [a], Chunxue Yang [a], Jianhong Wang [a], Zhiling Zhao [a]

[a] *Baize Institute for Strategy Studies, Southwest University of Political Science and Law, Chongqing, China*
[b] *School of International Relations, Sun Yat-sen University, Zhuhai, China*
[c] *Chinese People's Public Security University, Beijing, China*
[d] *Sichuan Police College, Luzhou, China*

A R T I C L E I N F O

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A B S T R A C T

Research purpose: This study aims to outline the fundamental status of the German academic community's research in the field of renewable energy and to foster collaboration between China and Germany in this area.
Research methods: This study examines documents published by German scholars from 2008 to 2023, which are part of the "Web of Science (WOS) Core Collection" database and related to renewable energy issues, using the bibliometric visualization tool CiteSpace 6.2.R6.
Research conclusions: The study examines the co-occurrence and burst of keywords, changes in publication volume, international collaboration networks, research institution collaboration networks, and researcher collaboration networks. It concluded that: (1) German academic research in the field of renewable energy can be divided into three phases: nascent (2008–2014), surge (2015–2021), and decline (2022–2023). (2) The Helmholtz Association and Reinhard Madlener, among other prominent institutions and academicians, are responsible for the close cooperation among personnel and institutions, the significant leading effect, and the emphasis on cutting-edge topics. Research in this field notably focuses on cutting-edge issues like life cycle assessment and developing countries. The study observes a transition in research concentration from macro to micro perspectives. In the context of a global collective response to climate change, the analysis of the German academic community's overall situation will enhance the collaboration between the two countries in the field of renewable energy research.

1. Introduction

Over one hundred nations worldwide have embraced the objective of limiting global warming to 2 °C or below (relative to pre-industrial levels) as a fundamental concept to mitigate the risks, impacts, and damage caused by climate change [1]. In the midst of the global transition towards sustainable energy and heightened emphasis on addressing climate change, the progress and application of renewable energy technology have emerged as significant topics of mutual concern among influential nations. Germany, as a

* Corresponding author.
** Corresponding author.
E-mail address: thzthu@126.com (H. Tu).

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leader in Europe's industrial and technological progress, engages in research and applies methods in renewable energy. These efforts serve as a guiding light for Europe and other regions, significantly impacting worldwide energy transformation and environmental conservation. Germany has a rich history as a dominant force in industry and technology in Europe. Its industrial production has traditionally been highly dependent on energy, particularly coal-fired and nuclear power. However, in addition to its strong industrial base represented by the conventional automobile industry, the German government has shown impressive vision and resolve in developing and executing national energy transition programs. In 2000, Germany introduced the Renewable Energy Sources Act (Erneuerbare Energien Gesetz, EEG), with the aim of promoting the economic advantages of renewable energy production [2].

In 2010, the Federal Ministry of Economics and Technology, in partnership with the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, released the "Energy Concept: for an Environmentally Sound, Reliable, and Affordable Energy Supply." The aim of this proposal was to transform Germany's energy system into an effective, sustainable energy-oriented, low-emission, and free from nuclear power system [3]. Germany amended the Renewable Energy Sources Act from 2021 to 2023, with the objective of achieving an 80 % share of renewable energy in electricity consumption by 2030 [4]. An analysis of these documents underscores Germany's commitment to substituting conventional energy sources with renewable alternatives. The German government has maintained a longstanding dedication to conducting research on renewable and clean energy technology. Furthermore, it has actively facilitated the expansion of the renewable energy industry through the implementation of well-planned energy policies. German research in renewable energies has flourished due to strong state backing, positioning Germany as a notable global leader in this field.

China, as a prominent participant in the advancement of renewable energy, has witnessed the emergence of electric vehicles and photovoltaic power generation as prominent goods in the renewable energy sector, both inside the country and worldwide. China and Germany have significant shared interests and opportunities for collaboration in the field of renewable energy development. The Chinese academic community lacks a clear understanding of various aspects of German academic studies on renewable energy issues, such as the status of international cooperation, collaboration among domestic research institutions, leading research institutions, networks for research personnel cooperation, citation networks, research hotspots, and research frontiers. Therefore, it is crucial to methodically arrange the current research progress on renewable energy matters within the German academic community in a scientific manner. This will enable a more profound comprehension of the situation in Germany and foster collaboration between research institutions from both countries on renewable energy topics.

In order to gather ideas from related research and establish parallels, a search was carried out in the Web of Science Core Collection using the terms "Germany," "renewable energy," and "bibliometric," resulting in 225 outcomes. However, upon further scrutiny, it was discovered that the majority of these research concentrated on particular subtopics within the realm of renewable energy, such as biofuels, wind power, and effective energy storage [5–7]. Some studies combine renewable energy with issues such as human capital, economy, and energy poverty [8–10]. We discovered a limited number of focused investigations on Turkey or Russia, but, we did not come across any extensive analysis on Germany's renewable energy industry [11,12]. In order to expand the range of the search, a search was performed on Google Scholar using the terms "German," "bibliometric," and "renewable energy." Although a search yielded 17,500 results, there is a lack of bibliometric studies that particularly examine the situation of renewable energy research in Germany. Paweł Kut and Katarzyna Pietrucha-Urbanik performed a comparative analysis of renewable energy research in Poland and Germany using data from the Web of Science database (WOS) [13]. Nevertheless, this study has two primary deficiencies: Firstly, the text lacks depth since it just offers a basic overview of annual publication trends, research institutions, and research hotspots without giving thorough analysis. Furthermore, the research design is rudimentary, lacking a comprehensive description of the data gathering and cleansing procedures. Adam Sulich and Tomasz Zema did a bibliometric analysis of Germany's energy transition as well [14]. Nevertheless, the data source utilized by the authors of that study was the Scopus database, which differs from the data source employed in this study. Furthermore, their research primarily concentrated on the shifting hotspots of the energy transition, without conducting analysis in other domains.

Peter Yang performed a bibliometric analysis on 1225 publications pertaining to Germany's energy transition spanning from 1982 to 2022. The study delineated the research process into three distinct stages: visual analysis, manual analysis, and focused review. It provided a clear identification of many technological difficulties and viable solutions in Germany's energy transition [15]. Yang's study focuses mostly on the difficulties associated to urban expansion in Germany's energy transition, with just a tiny section dedicated to examining the current situation of German academics. The report primarily examines the present state and regulations governing the shift towards urban energy in different cities across Germany.

In addition, literature was discovered that examines Germany's renewable energy challenges, including comparative research on renewable energy policy in Brazil, Austria, Japan, the United States, and Germany [16,17]. The majority of other literature merely briefly touches upon Germany's pertinent conditions when examining particular matters, with only a handful offering a methodical and all-encompassing examination of the research conducted by German academia in the realm of renewable energy.

According to the review provided, numerous researchers have made efforts to examine this subject from different perspectives. However, the current literature continuously fails to provide a thorough and detailed examination of the research conducted by the German academic community on renewable energy matters. This difference also impedes collaboration between foreign nations and German academia. The study tries to specifically address this problem, highlighting the significance of this study.

Prior to continuing, we have chosen to structure our study based on the following inquiries: what is the present condition of research on renewable energy-related matters in German academia, and what are the prominent topics that could potentially guide future research endeavors?

This study uses bibliometric techniques to examine research conducted in renewable energy within German academic institutions from 2008 to 2023. Specifically, this study offers the following contributions: (1) This analysis examines German scholars' publication patterns on this particular topic over several time periods. It also evaluates the areas of research that have received significant attention, as well as the notable literature produced at each stage. (2) This document provides a comprehensive overview of the collaboration between German academic institutions in the field of renewable energy. It identifies the prominent research organizations and researchers involved, as well as the primary research areas and focal points. Furthermore, it examines the collaboration between Chinese and German scholars, focusing specifically on the perspective of Chinese academia. (3) It integrates the compiled literature data with research trends to suggest possible future research directions.

The following portions of this study are organized in the subsequent manner: Section 2 provides a thorough elucidation of the research design, including the selection of research tools and databases, as well as the procedures for gathering and refining the data. Section 3 provides a thorough analysis of the current state of research. This includes an investigation into the patterns of publication at various stages, a critical evaluation of important literature, and an examination of the collaboration between prominent research institutions and researchers. The article also explores study themes and focal points, such as keyword co-occurrence analysis, clustering, and the temporal distribution and creation of topics. Section 4 provides the research conclusions, which succinctly outline the primary discoveries of this study. Section 5 offers a comprehensive analysis that highlights the key differences, advantages, limitations and progress made in this research when compared to other similar studies. Section 6 providing suggestions for further research.

2. Research design

2.1. Selection of research tools

Scientific research is confronted with the challenge of processing and analyzing immense quantities of data in the era of data explosion. Traditional manual analysis methods are not only inefficient but also incapable of managing large datasets in the face of the unprecedented growth in research outputs within the same field. Moreover, the insufficiency of a narrow disciplinary viewpoint and the increasing intricacy of scientific investigation necessitate modern research tools that can elucidate the interrelationships among different research areas, thus facilitating interdisciplinary research and collaboration. These technologies streamline complex scientific networks, research patterns, and locations into user-friendly charts and images, making it easier for researchers to analyze and understand data. Additionally, they enhance the accessibility of scientific discoveries to the general public. International collaboration between a variety of academic institutions and academicians is particularly valuable for studying renewable energy-related issues, particularly in the context of this study. The utilization of bibliometric analysis, which is based on knowledge graphs and visualization technology, offers an objective panoramic analysis of centers and developmental trends in the field [18–23].

This requirement has established the groundwork for the development of visualization research tools, including CiteSpace. CiteSpace provides precise, data-based analyses as a quantitative analysis instrument, thereby reducing the interference of subjective biases. It generates dependable statistical analysis outcomes by utilizing algorithms to process substantial quantities of data. This helps researchers rapidly understand the essential information regarding research trends, hotspots, collaboration networks, and co-citation counts in their field by presenting it in a more intuitive visual format. The co-authored book "CiteSpace: Scientific Text Mining and

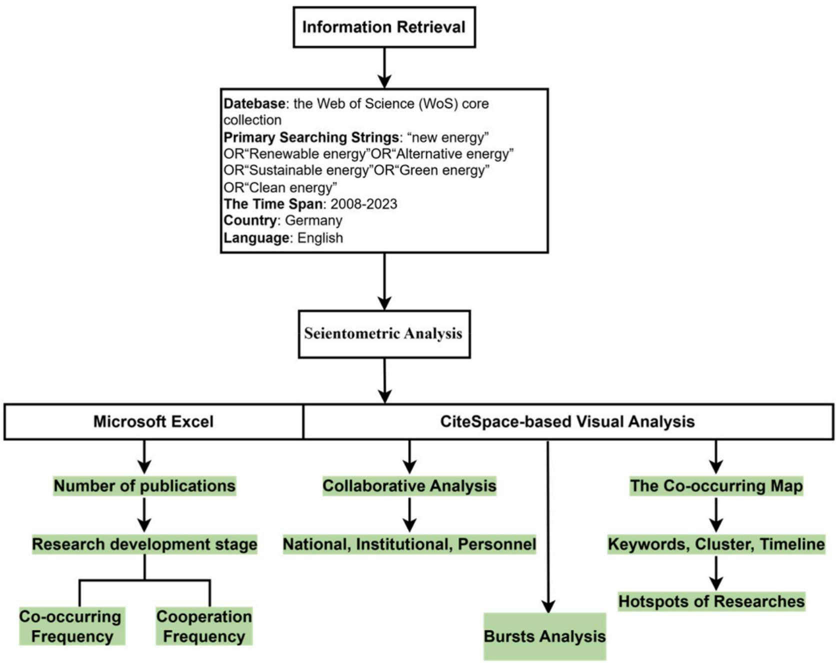

Fig. 1. Study design.

Visualization" by Chao-Mei Chen, a scholar of Chinese descent at Drexel University in the United States, and Li Jie, a deputy researcher at the Documentation and Information Center of the Chinese Academy of Sciences, provides a comprehensive overview of the design principles, operational processes, and usage methods of the CiteSpace research tool. The utilization of the CiteSpace tool for data analysis and visualization analysis effectively presents a greater number of scientific research results [24].

CiteSpace is more comprehensive in terms of functionalities, has a data interface that is more suitable for systematically organizing literature on the WOS website, and has a clearer operational logic, despite the fact that VOSviewer, Bibexcel, and Nvivo are similar software. Consequently, CiteSpace is the primary instrument chosen by this study for the analysis of the research status of renewable energy issues in the German academic community. The CiteSpace software has been updated to the advanced version 6.2.R6 (64-bit) Advanced, as of the writing of this paper. This software is employed in this study to analyze the situation regarding renewable energy research in the German academic field. The primary design procedure of this study is the following (see Fig. 1).

2.2. Selection of databases

It is evident that the quantity of various literature databases is quite substantial, including prominent ones such as Scopus, JSTOR, Taylor & Francis Online, and the WOS, among others, after analyzing internationally renowned primary databases. Nevertheless, the WOS is the database with the fewest limitations when factors such as the volume and coverage of data, the influence of the database, and the proportion of cutting-edge literature are taken into account. This platform is capable of accommodating the requirements for data capture across interdisciplinary domains and over extended periods of time, with a total of more than 2.2 billion referenced citations. Mastery of the research trends and prospective hotspots within a specific research domain is facilitated [25]. The WOS prioritizes indexing influential publications, particularly in the fields of natural and social sciences. While Scopus provides a wider range of coverage, the journals included in Web of Science often have greater status and influence among the academic community.

Subsequent investigation revealed that the other databases had lower literature counts and their citation data interfaces were incompatible with the CiteSpace software used in this research, thereby failing to satisfy the study's requirements. Consequently, it is possible to infer that the literature contained in the WOS database adequately covers the areas and subjects of renewable energy research within the German academic community. A thorough comprehension of the current state and primary areas of focus in renewable energy research within the German academic domain can be achieved by analyzing the data obtained from this database. Consequently, the WOS is selected as the primary source of research data in this article.

2.3. Scope of data collection

The Kyoto Protocol, which is designed to mitigate global warming by restricting greenhouse gas emissions in developed nations, establishes a timeframe for emission reductions from 2008 to 2012. The European Union is obligated to reduce its contribution by 8 % [26]. In 2008, Germany made changes to the Renewable Energy Sources Act (EEG-2009), significantly expanding its provisions from 12 to 66. This amendment resulted in the establishment of a more comprehensive framework [27]. In that year, several regulatory documents were put into effect to encourage the growth of the renewable energy sector. These included the Renewable Energy Production Promotion Ordinance (SDE), the General Rules for Energy Subsidy Allocation no.1313/2007, and the Solar Cell Government Subsidy Rules no.2009:689 [28]. Furthermore, the International Climate Initiative was initiated by the German Federal Ministry for the Environment with the objective of increasing the utilization of renewable energy and decreasing carbon emissions [29]. Germany achieved the Kyoto Protocol's reduction targets ahead of schedule in 2008, with a total of 945 million tons of greenhouse gas emissions. Given the aforementioned, it is regarded appropriate to commence the data collection range for this study in 2008. Consequently, this study analyzes the research outcomes associated with renewable energy issues that German scholars have produced from 2008 to 2023, as documented in the WOS. This encompasses the examination of hotspots in renewable energy research within the German academic community, major research institutions, international cooperation networks, co-cited authors, and co-cited literature networks, with the objective of facilitating improved Sino-German exchange and cooperation on renewable energy issues.

It is crucial to emphasize that the data collection procedure was designed to accurately reflect the fundamental situation and frontier hotspots of the German academic community's research on renewable energy issues, while also satisfying the data requirements of this study. Despite their profound affinity for the German language, German scholars do not hesitate to employ English, particularly in international exchanges and scientific research collaboration. The WOS typically contains the primary findings of German scholars who are engaged in international cooperative research on renewable energy issues. This study predominantly collected research outcomes written in English by German scholars, representing the research level of the German academic community in this field, in accordance with the research theme of this study and the characteristics of the WOS database. The scientific integrity and representativeness of this study are not impacted by the selection of English as the literature language search scope.

2.4. Data cleaning

The "Core Collection" database of the WOS contains the most prestigious academic journals, books, and conference records in the natural sciences, social sciences, arts, and humanities. It offers comprehensive bibliographic information for research analysis." The most recent research findings on renewable energy issues in the German academic community are effectively covered in this collection of high-level literature. In addition to the term "Renewable energy," equivalent terms include "New energy," "Alternative energy," "Sustainable energy," "Green energy," "Clean energy," and "Eco-friendly energy." After conducting a search of these terms, it was discovered that, with the exception of “Eco-friendly energy,” each term produced a significant number of documents. Consequently, all phrases except “Eco-friendly energy” were adopted as search keywords. Quotation marks were inserted around the search keywords to guarantee that they were identified as complete phrases rather than individual words. The search keywords were “new energy,” “renewable energy,” “alternative energy,” “sustainable energy,” “green energy,” or “clean energy,” resulting in a total of 34,536 documents. There were only 30 documents in German, and a very small number were in other languages. This supports the assertion that the scientific integrity and representativeness of this study are not compromised by the use of English-language documents as the data source, as previously stated.

The initial round of selection yielded 34,443 results by restricting the document language to English. These documents encompass a diverse array of fields, such as engineering, energy fuels, chemistry, materials science, physics, biochemistry, microbiology, computer science and artificial intelligence, theology, political science, and history. They encompass 15 types of documents, including articles, review articles, conference proceedings, and book reviews. A total of 34,357 results were obtained in the second round of selection, following the cleansing of data outside of the research period and the restriction of the timeframe to 2008 to 2023. It was also noted that the volume of literature in this field was minimal prior to 2008, but it encountered a substantial increase starting in 2008. This observation further substantiates the rationale for choosing 2008 as the starting point for the timeframe. Nevertheless, the data still contained results from more than one hundred irrelevant countries, including the United States, the United Kingdom, and France. Consequently, in the third round of selection, the country was restricted to “Germany” in order to more accurately represent the research outcomes of the German academic community, resulting in 2554 remaining results.

The remaining 2554 valid entries essentially cover the actual data of research on renewable energy issues by the German academic community from 2008 to 2023, fulfilling the requirements of this study, following the aforementioned data cleaning steps (see Table 1).

3. Bibliometric results analysis and visualization

The timeframe was selected from January 2008 to December 2023, with time segments set to one year, after the necessary Java environment was established for CiteSpace. The G-index is a metric that is used to evaluate the influence of a scholar or a collection of documents. G-index is a metric for measuring the impact of a scholar or a collection of documents; K value is used to define the number of neighbors considered for each node in clustering analysis; “Top N” selects a fixed number of the most significant items, while “Top N %” selects a percentage of the most significant items based on citation frequency or other criteria. The G-index K value was set to 25, the Top N value to 50, and the Top N% to 10 % in the node selection method area. Subsequently, the establishment of these fundamental parameters will be followed by the adaptation of various clustering nodes and thresholds to meet the diverse analytical requirements. Visual analyses will then be conducted accordingly.

3.1. Publication volume analysis

The time series distribution of literature is a critical method for analyzing the status and trends over time in a research topic [30]. The current state of research in the field and future research prospects can be predicted by statistically analyzing the number of papers published annually [31]. CiteSpace’s “Remove Duplicates” feature was employed to deduplicate local files and tabulate annual publication volumes in order to account for fluctuations in the volume of publications on renewable energy issues by the German academic community from 2008 to 2023. The following figure (see Fig. 2) illustrates the temporal variations in publication volume, as indicated by the software output. The time distribution of publication volume in this study field is depicted in Fig. 1, which divides the field into three phases: the embryonic phase (2008–2014), the expansion phase (2015–2021), and the decline phase (2022–2023). In general, the volume of publications has increased consistently since 2008, with a brief dip in 2014, followed by a subsequent increase until it reached a peak of 361 publications in 2021. Subsequently, it experienced a two-year decline to 205 publications in 2023, although it has maintained a relatively high level. Nevertheless, the German academic community has demonstrated a significant interest in renewable energy issues, as evidenced by the consistent increase in the volume of publications on this subject over the past decade. The data foundation for this study is also established by the extensive literature.

Table 1
Data retrieval and cleaning process.

Category	Limitation	No. of refined documents
Data Sources	Select “Core Collection”	
Retrieve location	Select “All fields”	
Theme scope	Search(“new energy”OR″Renewable energy”OR“Alternative energy”OR“Sustainable energy”OR“Green energy”OR“Clean energy”)	34536
Language	English	34443
Time scope	2008–2023	34357
Country	Germany	2554

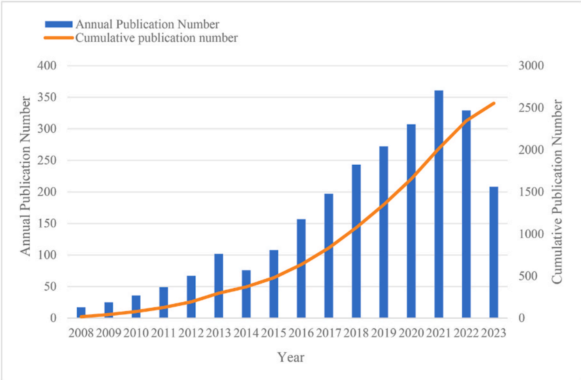

Fig. 2. Changes in the number of publications on renewable energy research in Germany.

3.1.1. *Embryonic phase (2008–2014)*

The discipline experienced a slow pace of development from 2008 to 2014. This phase is distinguished by a gradual but consistent increase in the quantity of publications, which experienced a decline in 2014. This phenomenon implies that the discipline, which gradually attracted scholarly attention, remained immature, with research topics and methodologies still in the exploration and development phase. The investigation scope encompassed a total of 372 documents during this period. The primary concentration of this era's research was on topics such as electricity loads, power generation, and power grids.

Published in 2010, the study on the impact of feed-in tariffs (FITs) on renewable energy investments by Toby Couture and Yves Gagnon had the highest co-citation count at 13. The primary contention of this study posits that FITs represent the most efficacious strategy for facilitating the expeditious and enduring implementation of renewable energies. The text examined the benefits and drawbacks of different FIT models and their impact on both society and investors [32]. Manuel Frondel and his colleagues conducted a study that examined the economic consequences of encouraging the use of renewable energy technology in Germany. It was found that the country's renewable energy laws, including the feed-in tariff schemes, did not successfully utilize the required market incentives to ensure the cost-effective and viable integration of renewable energies into the country's energy mix [33].

Matthias Kalkuhl and colleagues conducted an investigation into the potential of a combination of policy tools to advance renewable energy technologies. They found that carbon pricing alone could result in costly lock-ins into non-learning energy technologies, and that the energy sector is susceptible to lock-ins due to the high substitutability of energy [34]. Staffan Jacobsson and colleagues conducted a study of the EU's renewable energy support policies through specific cases. Their findings indicated that the current EU policies were inadequate to represent the future trajectory of renewable energy technology development in Europe and should be redesigned [35]. It was anticipated that global greenhouse gas emissions would be reduced by half by 2050, as stated in a G8 communiqué [36].Malte Meinshausen and colleagues established a correlation between the consumption of fossil fuels and the objective of preventing global warming. They determined that in order to prevent a 2 °C increase in global temperature by 2100, only approximately one-third of the exploitable reserves of oil, natural gas, and coal could be consumed [37].

In this period, there was a rise in the number of researchers who concentrated on the significant role of renewable energy generation in mitigating climate change and reducing carbon emissions.

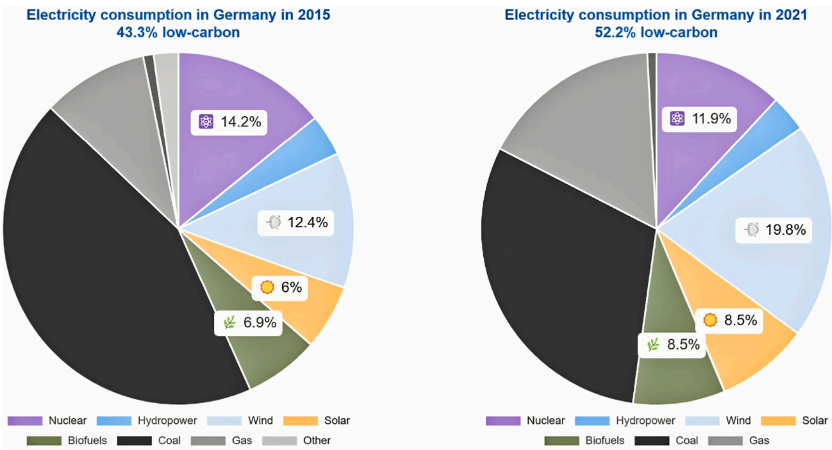

Fig. 3. Changes in the electricity mix in Germany (2015–2021).

3.1.2. Explosion phase (2015–2021)

The number of publications underwent a significant surge during this time frame, rising from 108 in 2015 to a peak of 361 in 2021, with an average yearly growth rate of around 22.28 %. Despite the COVID-19 pandemic that began in early 2020, the number of publications continued to rise. This implies that there is a delay between the conclusion of research and the publication of a paper. The challenges posed by the pandemic in terms of personnel mobility and apparatus use have not yet had an impact on the quantity of publications within academic research.

The energy structure of Germany underwent accelerated changes, as illustrated in the figure for 2015–2021. The combined share of nuclear energy, hydropower, wind power, solar power, and bioenergy - five renewable energy sources - increased from 43.3 % to 51.6 %, while the share of traditional fossil fuels, coal and oil, decreased from 44.8 % to 31.6 % in its electricity structure. Furthermore, the proportion of natural gas increased from 9.7 % to 16.8 % (see Fig. 3) [38]. This is indicative of the increasing significance of renewable and sustainable energy sources in the nation.

Research subjects including community energy, coal phase-off, and power systems reflect these developments in the field of study within this discipline. Notably, from 2015 to 2021 community energy has kept a strong degree of research interest. It highlights small-scale renewable energy projects owned, run, and maintained by a range of communities—including cooperatives, non-profit organizations, community groups, and small businesses—including Its main goal is to help nearby populations move from importation of energy to manufacturing of their own.

After conducting an analysis of the Renewable Energy Directive (RED II) in practice, Christina E. Hoicka and other scholars determined that the Energy Transition requires the resolution of the complementarity of renewable energies, spatial organization of resource potential, demographics, resistance from existing businesses, and inclusion of traditionally marginalized groups with financing and ownership models [39]. In an analysis of the impact of various regulatory models on the expansion of transmission networks, Jonas Egerer and other researchers proposed that incentive-based regulation may be more effective than cost-based regulation in the context of the large-scale transformation of the power system toward renewable energies [40].

W. Fischer and other scholars conducted an analysis of stakeholders in the German energy transition process, identifying five controversial issues: the security of electricity supply, the increase in industrial and commercial electricity prices, the rise in consumer electricity prices, the impact of energy transition on employment, and the political agitation speed of energy transition on its actual implementation [41].

The field's research underwent a gradual maturation during this phase, with the focus transferring to the evaluation of renewable energy policies and the development of specific mechanisms for the large-scale promotion of renewable energy technologies. Germany's renewable energy policies and legislation were substantially improved by scholars' research.

3.1.3. Decline phase (2022–2023)

The publication situation during this period is distinct from that of the explosive phase, as it exhibits a substantial decline, with the number of publications falling from 361 in 2021 to 208 in a mere two years. The global COVID-19 pandemic may be a contributing factor to this phenomenon [42–45] The process of selecting a study title, finalizing it, and publishing it is a lengthy one. The number of published papers does not immediately reflect the negative effects of the pandemic, which include the temporary suspension of equipment and laboratory use, restricted personnel mobility, and the cessation of numerous research projects. Papers that were published during the pandemic were frequently finalized prior to its onset. The pandemic's effects may have authentically manifested as a sudden decrease in the number of papers during the 2022–2023 phase.

High-impact keywords, such as renewable energy communities, artificial intelligence, quality certification, and green hydrogen production, emerged in the field during this period. This indicates that academic research has transitioned from a focus on macro-level policy analysis to a more in-depth examination of the issues that arise from the application of technology in specific regions, as renewable energy technologies are increasingly implemented on a large scale in Germany.

Irmak Karakislak and other scholars conducted a case study analysis of the influence of political figures and social norms on wind energy projects in Bavaria, Germany. They found that administrative officials' support plays a crucial role in the success of wind energy projects. They also underscored the significance of timely and comprehensive public information dissemination during the project's implementation [46].

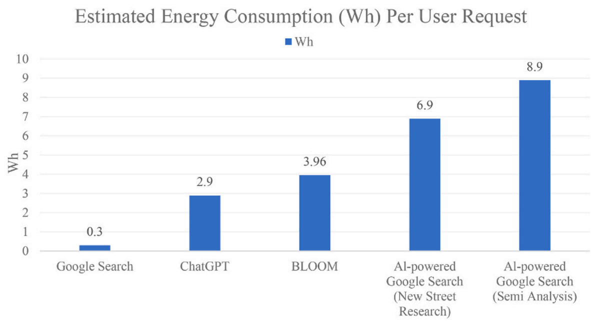

Fig. 4. Estimated energy consumption per request for various AI-powered systems compared to a standard Google search [29].

The field's research has also been revitalized by the rapid advancement of artificial intelligence technologies, as exemplified by ChatGPT. A substantial energy demand has been generated by the advancement of artificial intelligence technology. ChatGPT may require over 500,000 kWh of electricity per day to address approximately 200 million user requests, as indicated by a report published by The New Yorker [47]. Alex de Vries posits that artificial intelligence could consume 85–134 TW-hours (TWh) of electricity annually by 2027, which is approximately equivalent to the total electricity consumption of the Netherlands. This amount amounts to approximately 0.5 % of the current global electricity consumption [48]. The report also compares the electricity consumption of different artificial intelligence technologies with that of Google searches (see Fig. 4).

Scholars have been motivated to investigate the correlation between sustainable development and artificial intelligence (AI) due to the substantial energy consumption. Alexander Kopka and Nils Grashof conducted a study on the relationship between regional energy consumption in Germany and artificial intelligence. Their findings indicate that the impact of AI on energy consumption is significantly influenced by the industrial composition, technology, and regional environment. Consequently, they contend that it is not conducive to sustainable development to implement a "one-size-fits-all" subsidy for AI in order to resolve energy consumption concerns [49].

In recent years, with the increase in extreme weather events, some scholars have begun to question whether existing climate policies can achieve their intended goals. Suzuki, Masahiro, Jewell, Jessica, and Cherp, Aleh, examined the historical evolution of the power structures in the G7 and the EU to assess whether climate policies have accelerated the energy transition. They argue that current climate policies have insufficient impact and that incremental reforms are unlikely to achieve climate targets. The G7 countries and the EU must expand low-carbon electricity at five times the current rate and reduce fossil fuel use at twice the current pace [50].

Undoubtedly, close cooperation and enthusiasm among members play a crucial role in the progress of renewable energy projects. Effective planning beforehand also helps sustain incentives throughout the project's development. Radtke, Joerg, and Bohn, Nino S. studied the diversity and inclusiveness of members in certain German renewable energy projects. They argue that one key reason for the slow progress of some projects is the homogeneity of member structures, and they believe that enhancing diversity in membership composition can facilitate the advancement of these projects [51]. Jessica Weber, who studied three wind energy development cases in Germany and Sweden, found that proactive government planning helps provide effective incentives in the mid-to late stages of project development [52].

Overall, this period's research builds on the impacts of renewable energy technologies, which are increasingly permeating various aspects of society and taking a dominant role in the energy structure. Scholars have started to focus on specific issues brought about by new technologies like AI and electricity consumption. They also reflect on current energy policies, offering suggestions and analyzing the challenges faced by different countries in advancing energy projects. This field of research is continually maturing.

3.2. Collaboration network analysis

3.2.1. International collaboration network analysis

In order to evaluate the robustness of a country's research, it is imperative to conduct a comprehensive examination of its collaboration network graph. This analytical method offers valuable insights into the patterns of collaboration within the scientific exploration domain [53]. The node type (node) was set to country (Country) in CiteSpace to analyze the international collaboration on

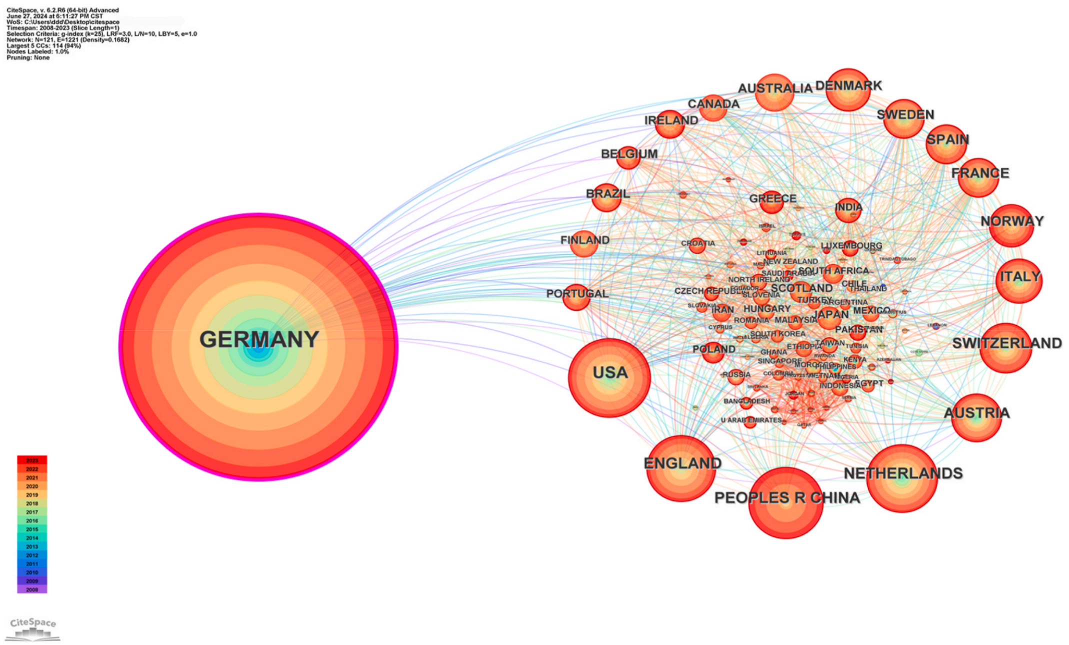

Fig. 5. International cooperation network for renewable energy research in Germany.

renewable energy research within the German academic community. The G-index values, K values, Top N values, and Top N% values were left unaltered. Nevertheless, the thresholds (c, cc, ccv) for the three time segments (early, middle, late) were individually set to (2, 2, 20), (4, 3, 20), and (4, 3, 20), respectively. The "visualize" button was then selected to generate the international collaboration network visualization for the German academic community on renewable energy issues, as illustrated in Fig. 5.("c" represents citation count, "cc" represents co-citation count, and "ccv" represents co-citation coefficient.) Given the large number of nodes, we set the threshold to 10 in the Control Panel to ensure the quality of the visualization results, thereby reducing the number of labels appearing. You can use this international collaboration network visualization to analyze the patterns and dynamics of international collaboration in this study field (see Fig. 5).

After completing the visualization with the country as the node type, the result screen showed N = 121and E = 1221. It's important to note that this does not mean that all the countries involved in the research had 1221 contacts in total; rather, it indicates that between 2008 and 2023, according to the parameters set for this study, Germany and another 120 countries had a total of 1221 contacts. Regarding the frequency of collaboration, Germany's universities and research institutions had the highest frequency, reaching 2540 times (see Fig. 5).

These institutions also engaged in extensive collaborations with research institutions in other countries, including the United States, the United Kingdom, China, the Netherlands, Australia, Switzerland, Italy, Norway, and other countries and regions. The most frequent collaboration was with the United States, reaching 292 times. The frequency of collaboration with the United Kingdom, China, and the Netherlands was relatively close, with China ranking third at 233 times, showing a significant gap with the United States and Germany. Countries with a collaboration frequency higher than 40 times were selected from the data to reflect the differences in collaboration frequency between countries (see Fig. 6), and an Excel table was created to view the specific situations of collaboration frequencies between different countries (see Table 2).

The observation indicates that the majority of the countries that are closely collaborating with Germany in renewable energy research are developed nations. China is the only developing country that ranks third with 233 instances of collaboration. This data underscores China's robust impetus in renewable energy research as a significant energy-consuming developing nation. China is making increasingly substantial contributions to the increase in the proportion of renewable energy in global energy consumption as a result of the rapid growth of its renewable energy industry, which includes photovoltaic products, batteries, and renewable energy vehicles [54–57]. The primary focus of American scholars who collaborate with German researchers is on the impact of renewable energy generation on the power grid through case studies, progress in storage technology, shortcomings in the development of electric vehicle technology, and core elements of the global energy transition, as indicated by the number of citations in the WOS database [58–62]. British scholars, on the other hand, explore the research domain from a variety of perspectives, including the range of study and academic connections, organized joint research, the relevance of Circular Economy (CE) practices to Sustainable Development Goals (SDGs), policy mixes for sustainability, and the similarities and differences between the UK and Germany in renewable energy transition paths [63–67].

Additionally, this study also performed a burst analysis of the international collaboration network in renewable energy research within the German academic community. The gamma (γ) value adjusts the sensitivity of burst detection, with lower values detecting more bursts and higher values detecting fewer bursts. By clicking the Burstness button in the Control Panel of the visualization interface, setting the γ value to 0.8 and the Minimum Duration to 2, then clicking Refresh, 8 bursts items were identified, sorted by

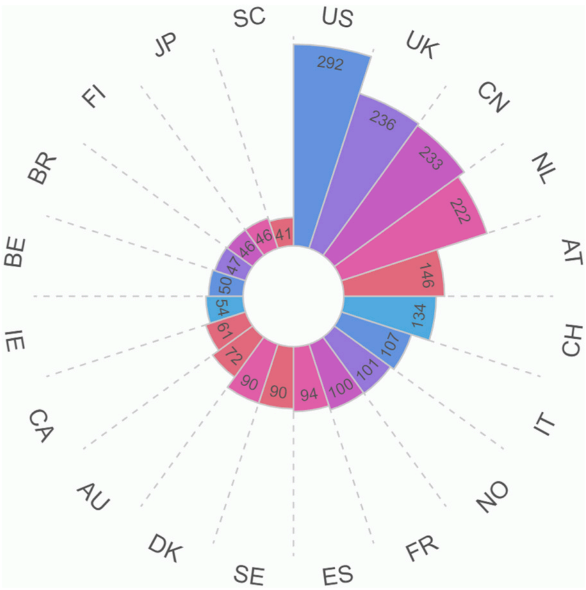

Fig. 6. Countries with a frequency of international cooperation greater than 40 times.

Table 2
Countries with more than 40 instances of international cooperation.

No.	Country	Frequency	No.	Country	Frequency
1	USA	292	11	Sweden	90
2	England	236	12	Denmark	90
3	China	233	13	Australia	72
4	Netherlands	222	14	Canada	61
5	Austria	146	15	Ireland	54
6	Switzerland	134	16	Belgium	50
7	Italy	107	17	Brazil	47
8	Norway	101	18	Finland	46
9	France	100	19	Japan	46
10	Spain	94	20	Scotland	41

burst strength from highest to lowest (see Fig. 7). Notably, citations from China have not been strong over the long term, but since 2021, there has been a sharp increase in citation strength, with a burst strength reaching 21.71, far surpassing other countries. It's important to note that the γ value setting only affects the number of bursts items appearing, not the burst strength. This data reflects an increasing collaboration in renewable energy research between the German and Chinese academic communities, undeniably a positive indicator for strengthening Sino-German renewable energy research cooperation [68].

3.2.2. Research institutions collaboration network analysis

According to the international collaboration analysis mentioned above, it's clear that German universities and research institutions are closely collaborating in renewable energy research. We set the node type to Institution in the CiteSpace initial interface to further analyze the collaboration among German universities and research institutions in renewable energy research while keeping all other parameters unchanged. However, the default setting results in too many nodes in the visualization, making it difficult to clearly discern the research institutions' collaboration overview. Therefore, we selected "Minimum Spanning Tree" and "Pruning sliced networks" in the pruning settings to minimize the appearance of nodes of lesser significance and prevent overly complex visualization results. Then, by clicking the visualize button, a network graph reflecting the collaboration among research institutions in renewable energy research within the German academic community was generated (see Fig. 8).

The visualization results indicate N = 462 and E = 812, meaning that from 2008 to 2023, within the scope of literature included in this study and after visualization analysis with the above settings, a total of 462 universities and research institutions have engaged in 812 instances of collaboration. However, there is a pronounced head effect in terms of the frequency of collaboration, with high frequencies of cooperation between top research institutions from various countries, represented by the Helmholtz Association and the Chinese Academy of Sciences, while many institutions have fewer than five or even just one instance of collaboration. This indicates a clear head effect in institutional cooperation, with a few top-tier research institutions forming close collaborative relationships. Only 22 research institutions have a frequency of collaboration exceeding 50 times. Clustering analysis of these institutions reveals that their research in this field is mainly reflected in 9 keywords (see Fig. 9): #0 social innovation, #1 integrated assessment model, #2 industrial demand-side flexibility, #3 developing state, #4 transmission grid extension, #5 soil erosion, #6 Europe's commitment, #7 palladium-catalyzed carbonylative synthesis, and #8 marine renewable energy. These nine keywords represent the fundamental directions of the German academic community in renewable energy research [69–74].

The top ten German research institutions in terms of collaboration frequency were selected to emphasize the collaboration situation among research institutions within the German academic community (see Table 3).

The statistics show that the top ten German universities and research institutions collaborating in renewable energy research are: Helmholtz Association, Technical University of Berlin, Fraunhofer Gesellschaft, Potsdam Institute for Climate Impact Research, Technical University of Munich, Karlsruhe Institute of Technology, Leibniz Institute for Catalysis at the University of Rostock, German Institute for Economic Research, RWTH Aachen University, and Helmholtz Center for Environmental Research. It is noticeable that among the top ten institutions in terms of collaboration frequency, six belong to cluster #0 with social innovation as the keyword, reflecting the German academic community's significant emphasis on social innovation-related issues and extensive collaborative research.

Furthermore, institutional collaboration in renewable energy research within the German academic community is quite concentrated, with very close cooperation among domestic research institutions represented by the Helmholtz Association, Technical

Fig. 7. Top 8 countries with the strongest citation bursts.

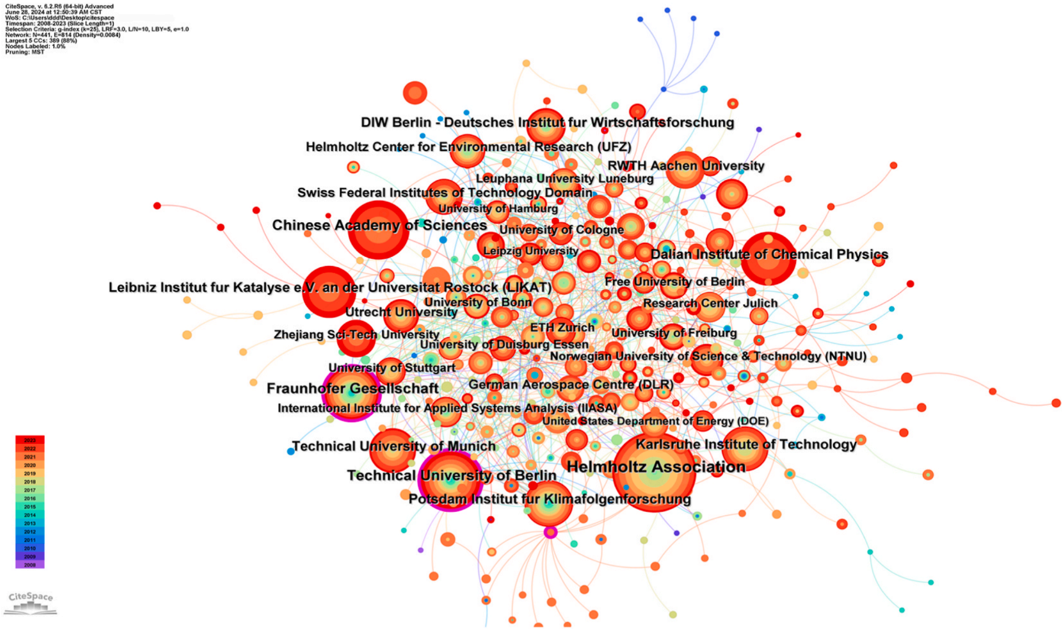

Fig. 8. Collaborative network of German renewable energy research institutes.

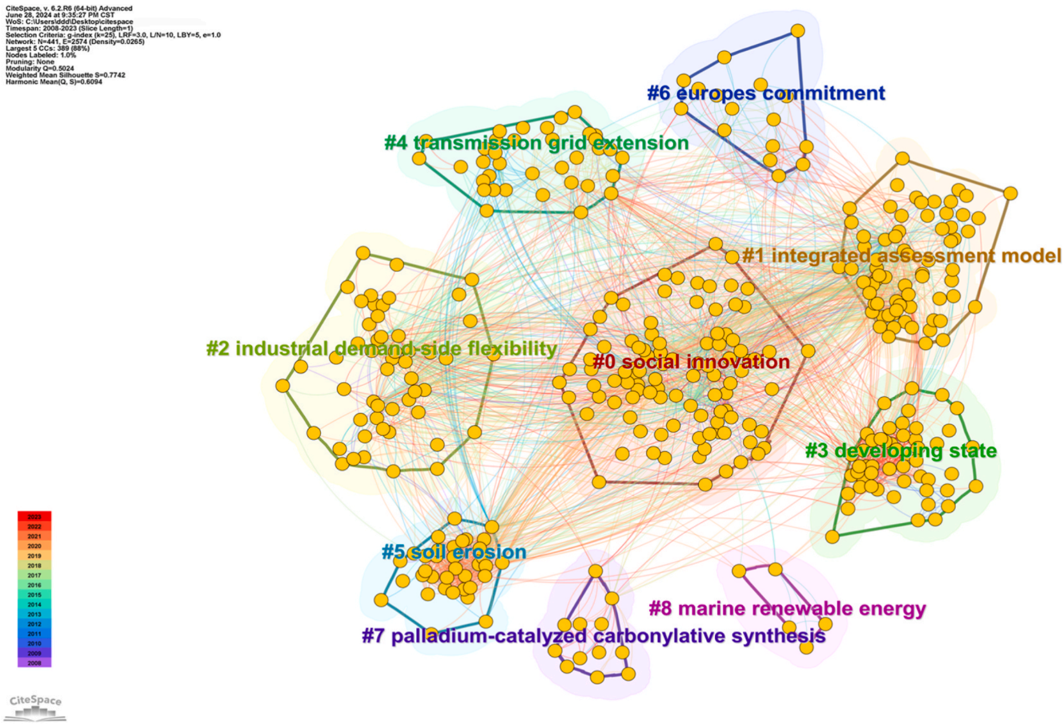

Fig. 9. Clustering of research institutions.

University of Berlin, and Fraunhofer Gesellschaft. The Helmholtz Association's strong research capabilities also allow it to significantly lead other institutions in collaboration frequency. These large research institutions, with their high frequency of collaboration, guide the direction of research on renewable energy issues in Germany.

Nevertheless, there is a discernible change in the frequency of collaboration among research institutions within the German academic community. 22 burst items were identified by selecting the Burstness icon in the Control Panel, setting the γ value to 1.5, setting the Minimum Duration to 2, and then refreshing(see Fig. 10).

Table 3
Top ten research organizations in terms of frequency of collaboration.

No.	Organization	Frequency	Cluster
1	Helmholtz Association	326	#0
2	Technical University of Berlin	161	#0
3	Fraunhofer Gesellschaft	142	#2
4	Potsdam Institut fur Klimafolgenforschung	123	#1
5	Karlsruhe Institute of Technology	115	#0
6	Technical University of Munich	113	#4
7	Leibniz Institut fur Katalyse e.V. an der Universitat Rostock (LIKAT)	113	#7
8	Deutsches Institut fur Wirtschaftsforschung	96	#0
9	RWTH Aachen University	87	#0
10	Helmholtz Center for Environmental Research (UFZ)	83	#0

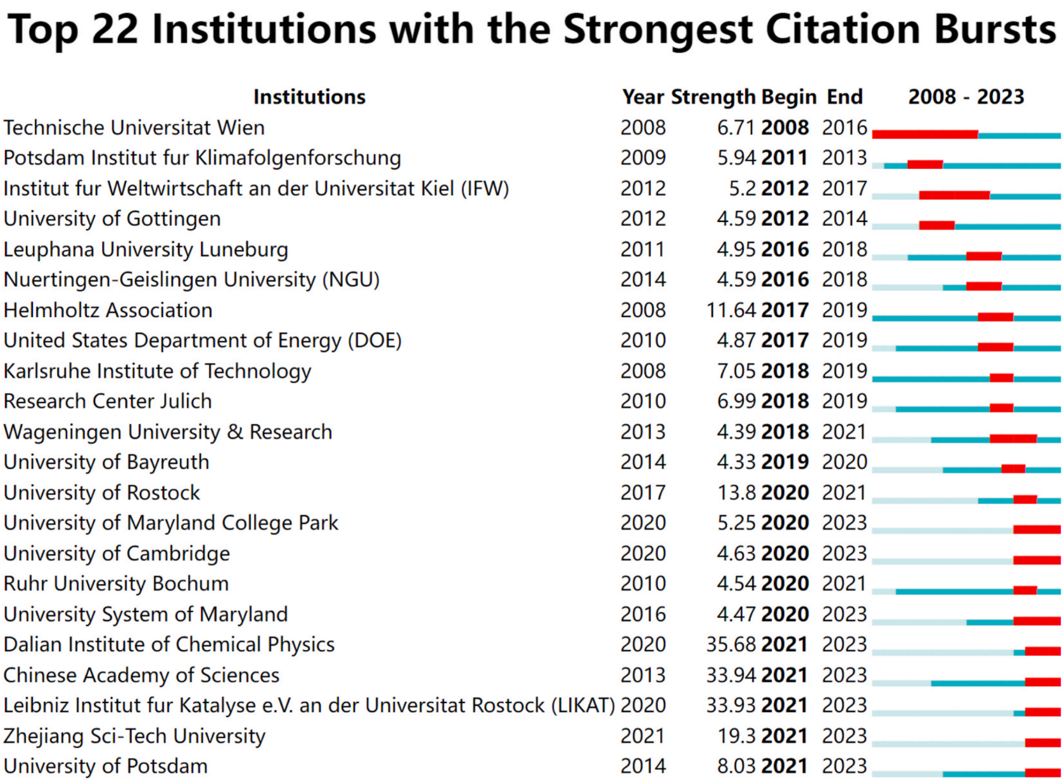

Fig. 10. Top 22 institutions with the strongest citation bursts.

It is evident from Fig. 10 that the German academic community has consistently favored collaborating with European universities or research institutions. Nevertheless, in 2021, a trend of collaboration between the German academic community and research institutions in China began to emerge. This trend included high-profile institutions such as the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, the Chinese Academy of Sciences, and Zhejiang Sci-Tech University. This change once more demonstrates the institutional collaboration between the Chinese and German academic communities, as well as their mutual interests and alignment in research directions on renewable energy research.

3.2.3. Researcher collaboration network analysis

To delve deeper into the collaboration among researchers in the German academic community on renewable energy research, the node type was set to "Co-authorship" in the CiteSpace interface. Due to the complexity of the default visualization results, the "Minimum Spanning Tree" was selected in the Pruning settings, along with "Pruning sliced networks" and "Pruning the merged network" to reduce the appearance of less significant nodes, simplifying the visualization results. After setting up, clicking the visualization button generated a researcher collaboration network map (see Fig. 11).

According to Fig. 11, there is a tight collaboration network among scholars in the German academic community on renewable energy research. The image evidences a broad division of numerous scholars into seven prominent groups, where different researchers collaborate closely. Also, these scholar groups typically include several influential scholars as core members. According to the study's

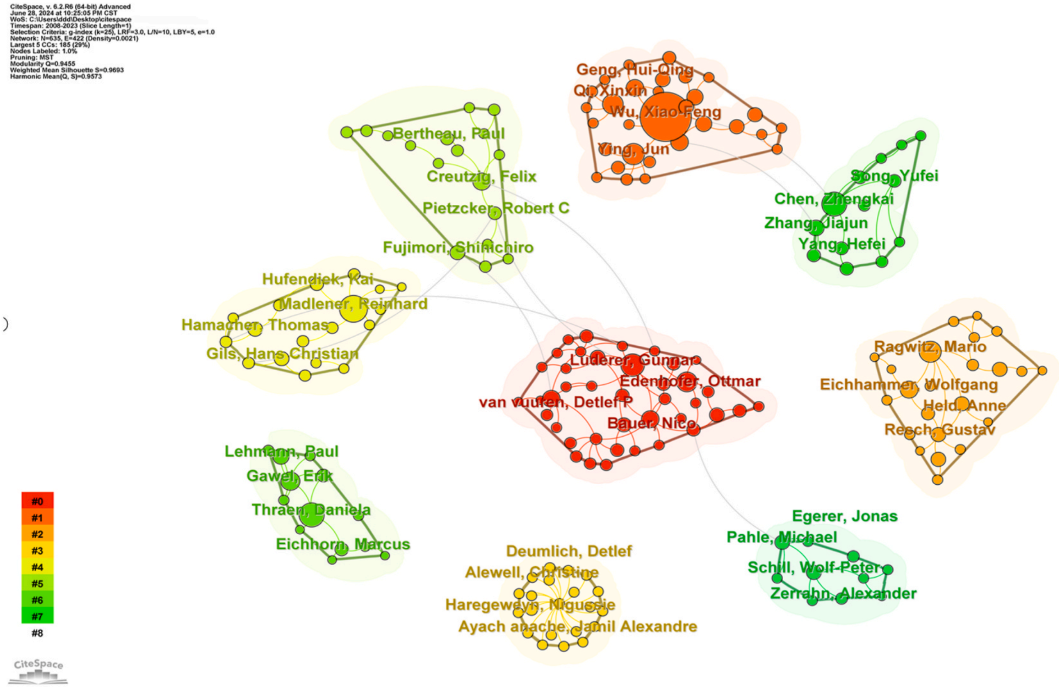

Fig. 11. Collaborative network of scholars.

collaboration frequency statistics, the top ten primary researchers in renewable energy research in Germany are as follows: Reinhard Madlener, Daniela Thrän, Gunnar G. Luderer, Mario Ragwitz, Johan Lilliestam, Carsten Herbes, Ottmar Georg Edenhofer, Valentin Bertsch, Wolf Fichtner, Erik Gawel [75–84]. These ten scholars, along with other researchers in their teams like Felix Creutzig and Wolf-Peter Schill, constitute the collaboration network in renewable energy research within the German academic community, as shown above. Notably, the largest among these scholar groups is the team involving Gunnar G. Luderer and Ottmar Georg Edenhofer. (central red part of the image)

The majority of these academics are affiliated with esteemed German universities or research institutions, including Gunnar G. Luderer from the Potsdam Institute for Climate Impact Research, Reinhard Madlener from RWTH Aachen University, and Daniela

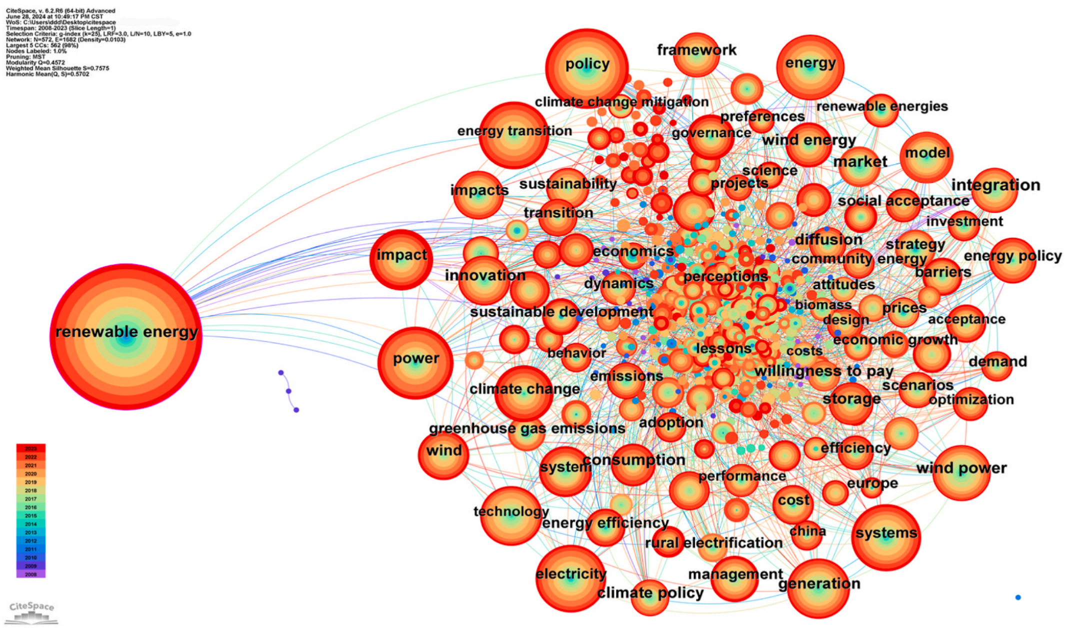

Fig. 12. Keyword co-occurrence network.

Thrän from the Technical University of Berlin. The direction of renewable energy research in Germany is spearheaded by these esteemed universities and research institutions, which have generated a plethora of advanced results and established a robust network of scholarly collaboration.

3.3. Hotspots in German renewable energy research

3.3.1. Keyword Co-occurrence analysis

Given that keywords concisely summarize research topics and reflect the focal points of prominent researchers, their frequent appearances are a critical indicator that reveals research hotspots in a certain field. Consequently, the co-occurrence network of keywords becomes an indispensable instrument for researchers who are investigating prevalent research themes within a particular domain [85].We set the node to "Keywords" in CiteSpace to analyze the research directions and frontiers in the field of renewable energy-related issues within the German academic community. We selected "Minimum Spanning Tree" in the Pruning settings, along with "Pruning sliced networks," and deselected "Pruning the merged network" without adjusting other parameters to avoid overly complex visualizations. We generated a keyword co-occurrence network after clicking the visualization button (see Fig. 12).

According to Fig. 12, under the specified parameters, there were 572 nodes with 1682 connections. Further filtering to exclude less frequently occurring nodes identified 22 keywords with co-occurrence frequencies of 90 or above. The keywords are listed in order from highest to lowest: renewable energy, policy, power, electricity, energy transition, energy, systems, technology, impact, generation, climate change, wind power, model, innovation, impacts, system, wind, energy policy, management, integration, wind energy, and framework(see Table 4).

CiteSpace's "cluster" function categorizes and aggregates keywords using a specific algorithm, distinguishing different clusters by color. This allows for an analysis of the main research areas in renewable energy issues within the German academic community. LLR (Log-Likelihood Ratio) is used to assess the significance of a term or feature within different document clusters to identify the terms that best represent each cluster. Applying the LLR algorithm, keywords were clustered based on their similarity [18].Clicking the cluster button yielded the visualization result shown in Fig. 13.

"Modularity Q" is a metric that evaluates the capacity of a network to be organically partitioned into distinct groups and the overall structure of the network. It is evident from the observation that the modularity Q value in Fig. 13 is 0.4572, which is greater than 0.3, suggesting a substantial clustering structure [86]. The Silhouette parameter, ranging from −1 to 1, evaluates the similarity of keywords within a cluster, and the average Silhouette value in this study is 0.7575, surpassing 0.7, indicating convincing clustering results. It's evident that German academic research on renewable energy can be divided into ten clusters, each summarized by a keyword representing the research area of its cluster, listed as follows in order of clusters #0–9: #0 developing countries, #1 life cycle assessment, #2 energy storage, #3 energy efficiency, #4 energy transition, #5 alkenes, #6 renewable energy, #7 policy mix, #8 CO2 abatement, #9 renewable energy sources. The primary areas and orientations of renewable energy research within the German academic community are broadly encapsulated by these ten phrases or words. It is important to note that cluster #0, which is tagged as "developing countries," is the most influential. This suggests that the German academic community perceives developing countries as having a substantial influence on the development of renewable energy technologies.

The nodes within this cluster are analyzed to reveal high-frequency keywords such as sustainable development, governance, rural electrification, and sustainability. This suggests that the German academic community has a precise understanding of the critical issues involved in the development and promotion of renewable energy technologies. Significant energy demands during their industrialization processes as well as conflicts between economic development and environmental preservation frequently result in technology, funding, and talent shortages in developing countries for renewable energy research. For example, Marquardt Jens, having conducted research on the promotion process of renewable energy policies in the Philippines, contended that the implementation of renewable energy policies is significantly impeded by unclear responsibilities, conflicting regulations, weak local capabilities, a lack of recognition of national intentions, and a lack of consultation [87]. The way developing countries address these issues significantly influences the global prospects of renewable energy technology applications. Furthermore, the German academic community dedicates itself to examining energy storage, energy efficiency, and energy conversion, as the resolution of these issues significantly influences the global adoption of renewable energy technologies [88–90].

Table 4
Keywords with a co-occurrence frequency of 90 or more.

No.	Keywords	Frequency	No.	Keywords	Frequency
1	renewable energy	856	12	wind power	134
2	policy	275	13	model	117
3	power	230	14	innovation	113
4	electricity	191	15	impacts	112
5	energy transition	191	16	system	105
6	energy	187	17	wind	104
7	systems	187	18	energy policy	97
8	technology	159	19	management	93
9	impact	158	20	integration	92
10	generation	152	21	wind energy	92
11	climate change	146	22	framework	91

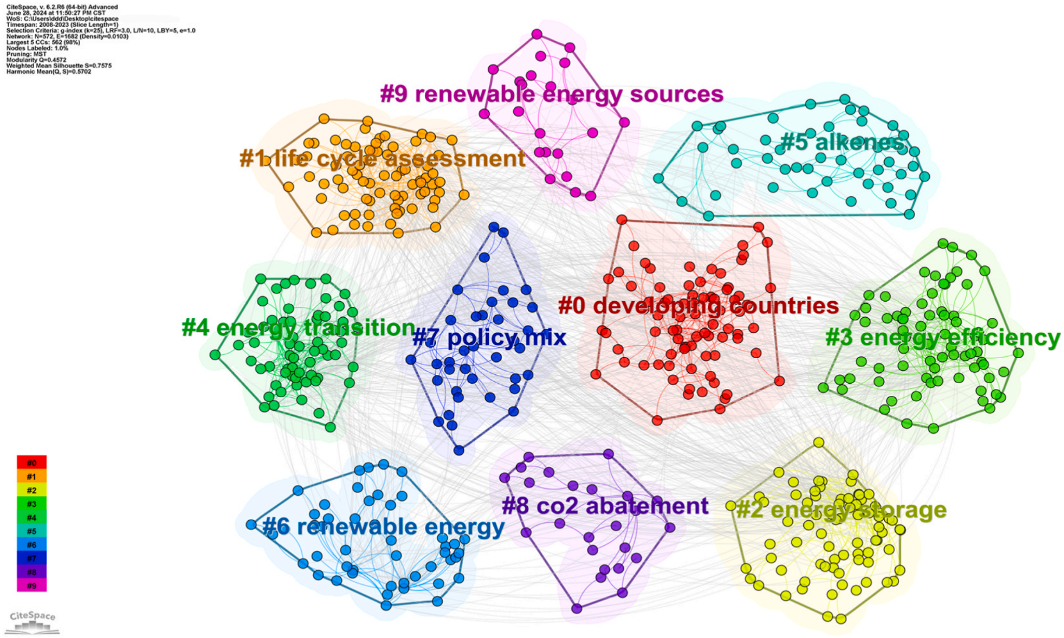

Fig. 13. Keyword clustering network.

3.3.2. Timeline analysis of research hotspots

We used CiteSpace's Timeline View function to visualize various clusters on a timeline and examine the most recent concentrations in renewable energy research within the German academic community. This analysis focused on the research frontiers of renewable energy research within the German academic community. After completing the clustering analysis, we selected the Timeline View function to produce a visualization of the keywords in renewable energy research by the German academic community from 2008 to 2023 along the timeline, without adjusting any parameters (see Fig. 14).

From Fig. 14, it is evident that cluster #0, labeled as developing countries, was the largest from 2008 to 2023. Issues related to developing countries have always been a focus of the German academic community's research on renewable energy, especially during the decade from 2010 to 2020. This period coincides with global industrial shifts to developing countries, significantly increasing their energy demand as they pursue extensive economic development. How to reduce energy consumption per unit of GDP while ensuring

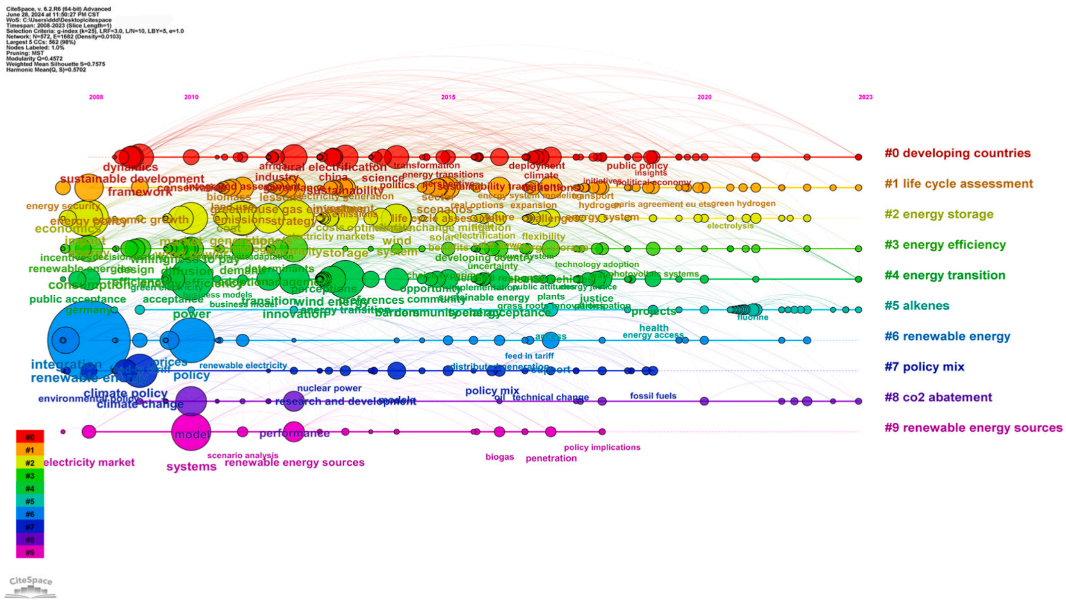

Fig. 14. Timeline view of renewable energy research hotspots in Germany.

continuous economic growth in developing countries has been a major concern for the German academic community [91–93]. Additionally, life cycle assessment (LCA), represented by cluster #1, has been a long-term research focus [94–97]. The continuous presence of cluster #1 nodes on the timeline underscores its longstanding importance in German research. However, fewer nodes on its timeline indicate a gradual decline in focus for the energy transition cluster after 2020. The cluster labeled alkenes (alkenes) has gradually become a research hotspot in recent years, with most of the literature within this cluster conducted by Chinese scholars in the field of chemistry. We need to conduct further analysis to ascertain whether a breakthrough technology has sparked this surge in interest. The policy mix cluster, #7, was particularly active from 2010 to 2020, a decade during which the German government released or amended a series of policies or regulations, such as the Energiewende (Energy Transition).

Nevertheless, the enthusiasm for this domain has diminished in recent years, aligning with the development and establishment of renewable energy-related regulations and legislation in Germany. The CO_2 abatement cluster, also known as the carbon dioxide abatement cluster, has experienced varying levels of interest over time, but it has recently garnered increased attention in the past two years. This tendency is likely linked to the worldwide increase in emphasis on carbon neutrality. The German government has taken aggressive measures in response to the issue. On May 12, 2021, the Federal Cabinet approved a new version of the Federal Climate Change Act, at the recommendation of Federal Environment Minister Svenja Schulze. The main components include achieving carbon neutrality by 2045, strategies to achieve carbon neutrality, and initiatives to decrease greenhouse gas emissions by 65 % by 2030 in comparison to 1990 levels [98]. Naturally, the German academic community closely follows the forefront of research, emphasizing the issue of CO_2 abatement.

China, being a significant contributor to carbon emissions, also has a community of scholars dedicated to researching this matter in order to identify efficient strategies for mitigating carbon emissions. Mingwei Lin and colleagues undertook a bibliometric analysis of material published between 2006 and 2021 in the domain of carbon neutrality. In order to meet China's carbon dioxide reduction goals, experts propose that it is crucial to not only decrease emissions, but also to boost "negative emissions" by utilizing carbon sinks and implementing carbon capture, utilization, and storage technologies [99].

Due to the reduced publishing period and limited influence of papers on developing subjects, the enormous volume of data can potentially inundate software-driven analysis. In this study, we performed a manual examination of 486 papers retrieved from the Web of Science database. The publications were sorted based on their citation count from 2022 to 2024, in accordance with the research criteria of our study. The investigation has identified geopolitical concerns and energy transition as emerging themes, possibly linked to the protracted conflict between Russia and Ukraine and the growing tensions between Palestine and Israel.

Wiertz, Thilo, Kuhn, Lilith, and Mattissek, Annika, conducted a study on the influence of the Russia-Ukraine conflict on Germany's energy transition. The analysis of news articles, interviews, and parliamentary statements since the start of the war has revealed that Europe's energy shortages due to the conflict have moderately impacted the energy transition agreement. However, it has stressed the need to accelerate the energy transition [100]. Hille Erik also conducted research on this topic, providing the first empirical evidence on the influence of geopolitical crises in energy-supplying countries on the development of renewable energy in importing countries. An analysis of energy trade data from 37 European countries between 1991 and 2021 revealed that geopolitical risks in the supplying countries frequently facilitate the proliferation of renewable energy in Europe [101].

Chinese academicians have recently integrated renewable energy research with the increasingly prevalent subject of artificial intelligence, a significant advancement. For instance, Lili Zhang and others used bibliometric methods to review the research on artificial intelligence and renewable energy, finding that AI-related technologies can effectively address the integration of renewable energy with power systems [102]. However, German academia has rarely combined the topic of artificial intelligence with renewable energy research. We found only one study that strongly correlated with the AI theme. This situation requires German scholars to pay close attention.

3.3.3. Keyword burst analysis

This article utilizes the burst detection feature of CiteSpace to ascertain the keywords that dominated research trends in specific years and to investigate the evolution of research focal points within the German academic sphere regarding renewable energy issues between 2008 and 2023. This instrument is employed to determine the temporal influence, intensity, and emergence of various keywords, as well as to identify the bursts term that is presently influencing renewable energy research.

The CiteSpace interface configures nodes to keywords without altering any other parameters. Subsequently, the visualization icon

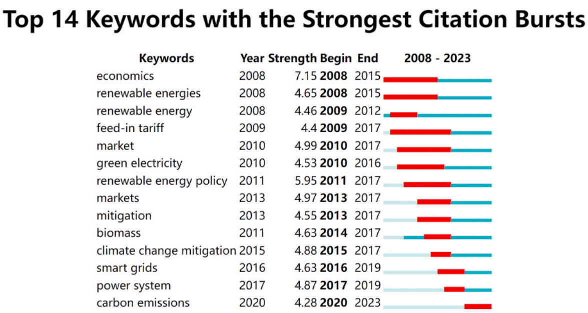

Fig. 15. Top 14 keywords with the strongest citation bursts.

is selected. In order to access the burst detection interface, the burstness button in the control panel is selected upon the visualization results' appearance. The default settings disclose as many as 78 bursts terms, the majority of which have a short duration and minimal impact because of the extensive volume of literature involved in this study. Consequently, they lack representativeness for research hotspots. In order to improve the representativeness of the bursts terms, it is imperative to raise the threshold for both duration and impact. Consequently, the γ value is adjusted to 1.5, and the minimal duration is set to 3, followed by a refresh. This results in 14 burst terms with robust representativeness that satisfy the requirements of this study. The subsequent results are obtained by clicking the visualization icon(see Fig. 15).

The 14 bursts terms are arranged in the following order of their occurrence: economics, renewable energies, renewable energy, feed-in tariff, market, green electricity, renewable energy policy, markets, mitigation, biomass, climate change mitigation, smart grids, power system, and carbon emissions.

Analyzing the results of the burst keywords reveals that the term economics appeared earliest and had the greatest impact, with a high intensity of influence from 2008 to 2015, and it continues to exert a significant impact to this day. We can interpret this outcome from two distinct perspectives. On one hand, the demand for renewable energy technologies emerged against the backdrop of massive economic activities consuming traditional fossil fuels, leading to high pollution and emissions.

Additionally, new demands on energy sources and environmental impacts emerged as economies, particularly China, transitioned from extensive growth models to high-quality development, with the goal of minimizing the environmental footprint of economic activities. This also explains why life cycle assessment became the second-ranked cluster in the previous cluster analysis. On the other hand, the economic feasibility of renewable energy technologies represents one of the major challenges in their development. Traditional fossil fuels, such as coal and oil, enjoy conventional advantages in extraction costs and convenience of use, whereas renewable energy technologies and derivatives, including wind power, bioelectricity, photovoltaics, and electric vehicles, often face higher research and development and production costs, making them more expensive for consumers. Government subsidies and policy support are essential for their survival. For the development and expansion of renewable energy technologies, addressing their economic viability is a critical challenge.

Beyond economics, recent years have seen the emergence of significant terms such as renewable energy, feed-in tariffs, and green electricity, which have significantly impacted the academic community. The figure shows that carbon emissions have become the most recent term to influence research since 2020. The preceding text offers an explanation for this phenomenon, attributing the heightened research interest in carbon neutrality and the development of the European Union Emissions Trading System (EU ETS) as drivers for the study of issues related to carbon emissions [103].

4. Results

This study analyzes the literature on renewable energy issues within the German academic community from 2008 to 2023, utilizing CiteSpace 6.2.R6 Advanced as the primary research instrument and obtaining data from the Web of Science (WOS) database's Core Collection. Visual analyses of the international collaboration network, research institution cooperation, research personnel collaboration, and recent research centers were conducted, with a detailed analysis of the results. The primary findings of this study are as follows:

4.1. International collaboration network

The international collaboration of the German academic community in the field of renewable energy research is extensive. Germany has established a cooperation network with 120 countries or regions in the literature examined in this study. The top twenty countries by frequency of collaboration are as follows: the United States, England, the People's Republic of China, the Netherlands, Austria, Switzerland, Italy, Norway, France, Spain, Denmark, Sweden, Australia, Canada, Ireland, Belgium, Brazil, Finland, Japan, and Scotland.

The frequency of 292 is the highest among all countries, and the collaboration with the United States is the closest. England follows with 236 collaborations, while China ranks third with 233, which is slightly less than England.

Following these nations, the Netherlands, Australia, Switzerland, Italy, Norway, and France each have over one hundred collaborations, while the remaining countries have fewer than one hundred, indicating a distinct decrease in frequency. This suggests that German academicians' research collaboration is primarily focused on countries with a high level of renewable energy research.

4.2. Leading institutions and scholar clusters

A series of universities and significant research institutions in Germany dominate research in this field. The following institutions are included in this list: the Helmholtz Association, Technical University of Berlin, Fraunhofer Gesellschaft, Potsdam Institute for Climate Impact Research, Technical University of Munich, Karlsruhe Institute of Technology, Leibniz Institute for Catalysis at the University of Rostock, German Institute for Economic Research, RWTH Aachen University, and the Helmholtz Center for Environmental Research.

Furthermore, the examination of research scholar collaboration demonstrates the same characteristics as the cooperation among research institutions, with a handful of prominent scholars exhibiting exceptionally high levels of collaboration. Additional cluster analysis indicates that German scholars engaged in renewable energy research can be classified into seven scholar groups, which establish a complex and organized cooperation network with these high-frequency scholars as key nodes and maintain strong internal connections.

The study also observes that Wu Xiaofeng, a Chinese scholar, is actively involved in close collaboration with German scholars. Consequently, the network of these Chinese scholars is an indispensable component of the visualization results. The positive trend of progressively enhanced collaboration between the academic communities of Germany and China is reflected in this.

4.3. Research hotspots and directions

Finally, this study identified 22 keywords with a co-occurrence frequency of over 90 after conducting a co-occurrence analysis of frequently appearing keywords to identify research directions and hotspots. Additional clustering analysis of these keywords identifies ten clusters, which are sequentially designated #0–9 as follows: renewable energy sources, policy mix, CO_2 abatement, renewable energy sources, energy storage, energy efficiency, energy transition, alkenes, and life cycle assessment. The primary disciplines and research directions within the German academic community on renewable energy research are succinctly encapsulated by these phrases or words.

This study also mapped these keywords along a timeline and discovered that the clusters labeled "developing countries" and "life cycle assessment" have a consistent high level of research intensity. On the other hand, the "CO_2 abatement" cluster has significantly increased its research intensity after 2020, likely due to the growing global focus on carbon neutrality.

Furthermore, this study conducted an analysis of the emergence of keywords, identifying 14 with substantial representativeness and influence. Each of these keywords denotes a location in the renewable energy research of German academia during specific years.

5. Discussion

In the introduction, we conducted a cursory examination of the current state of literature of a similar nature and identified its deficiencies. The content of this study indicates that there are three primary distinctions between this study and existing studies. The initial distinction is the investigation's focus. The internal state of German academia is not comprehensively examined in the majority of extant studies, which primarily focus on specific issues within Germany's energy transition. They frequently engage in comparative studies with other countries or analyze the current status and policy strengths and shortcomings of Germany's energy transition. In contrast, this study underscores the importance of conducting a comprehensive examination of the internal condition of German academia, which includes the distribution of research hotspots, the identification of significant research institutions and researchers, and the various levels of collaboration.

Secondly, the data sources are not consistent. The Web of Science database is utilized by fewer studies, while existing studies frequently depend on databases such as Scopus and ScienceDirect. Furthermore, this study incorporates a more extensive dataset than comparable studies.

Third, the selection of literature takes place within a distinct time frame. Some extant studies set their data collection starting point excessively far in the past. However, this study indicates that the majority of publications on renewable energy issues in German academia emerged after 2008. Prematurely establishing the starting point could introduce a temporal span issue. This study predominantly relies on data as of December 31, 2023, while some existing studies have limited research on data post-COVID-19. At the time of this paper's completion, we manually analyzed only 65 publications published since 2024. This study exhibits innovation and differentiation in its research focus, data sources, data volume, and time span in comparison to existing research, as indicated by these factors.

Additionally, the majority of comparable studies employ tools such as VOSviewer or other software for analysis, whereas this study utilizes the most recent version of CiteSpace (6.2.R6). CiteSpace is a comprehensive and powerful software that integrates the benefits of similar tools and introduces corresponding enhancements. This results in a greater variety of types and clearer visual outputs, thereby improving the effectiveness of bibliometric research. This study has an advantage in terms of instrument usage when compared to similar studies.

In conclusion, this study's most notable characteristic and advantage is its emphasis on the German academic community's research on renewable energy issues, as contrasted with comparable studies. The study delineates the data sources, provides a comprehensive explanation of the data collection and cleansing process, and outlines the detailed steps for analysis using Citespace, all using the most recent data. The study meticulously and thoroughly examines international collaboration networks, institutional cooperation networks, scholar collaboration networks, and changes in research centers. This study outlines a procedure that can replicate the study's results consistently. This study accomplishes its objective of offering a comprehensive examination of the current state of renewable energy research in German academia.

There are two primary constraints in this study. At first, it only used the WOS Core Collection database as its source of data. Although WOS is a reputable scientific literature database, it mostly comprises English-language journals, which may result in the exclusion of important non-English research. In addition, as WOS significantly depends on journal impact factors, the inclination of high-impact journals to publish certain types of research can affect the bias of research findings. Moreover, the labeling and classification approach used by WOS has the potential to inaccurately categorize important studies during interdisciplinary research, particularly in the field of renewable energy.

Furthermore, while bibliometric analysis can provide insights into broad aspects such as research patterns, the presence of keywords, and collaborative networks, it is not well-suited for comprehending the exact intricacies of study content, methodology, and empirical analyses. Furthermore, bibliometric studies may struggle to fully capture the complexities of transdisciplinary or nascent subjects. To address these constraints, future studies could expand the scope of data sources, extend the research duration, increase the depth and breadth of research content and technique, and conduct a more comprehensive analysis of the extent and caliber of international collaboration networks.

6. Conclusion

Based on the previous analysis, we anticipate that topics such as carbon emissions, carbon trading, artificial intelligence and energy consumption, and geopolitical crises may become significant areas of focus in terms of potential research hotspots under this theme. The carbon trading market in the European Union has been evolving for a number of years and is progressively improving. The carbon price in the EU is consistently increasing as carbon emission control measures continue to advance.

The release of ChatGPT-4 and ChatGPT-4o has revealed substantial technological advancements in large language models. Baidu's "Ernie Bot" and iFlytek's "Spark" models are both examples of the accelerated advancements in China's large model technology. Consequently, the advancement of artificial intelligence technology leads to a significant increase in electricity consumption. If a country extensively deploys AI technology in devices like smartphones and computers for localized use, it will have a significant impact on electricity consumption.

Nevertheless, our examination of German scholarly publications on renewable energy revealed a scarcity of articles that are closely linked to artificial intelligence. This is a promising area for substantial investment and attention in future study within German academia.

Despite the limited number of studies on the relationship between geopolitical crises and renewable energy, the ongoing stalemate in the Russia-Ukraine war, the escalating conflict between Palestine and Israel potentially spreading to Lebanon, and the continuous attacks on commercial vessels by the Yemeni Houthi movement suggest that the impact of geopolitical crises on renewable energy development will continue to be an important topic for the foreseeable future.

In conclusion, this study conducts a systematic review of the international cooperation, research institution collaboration, research personnel cooperation, research hotspots, and keyword emergence within the German academic community in the field of renewable energy by analyzing 2554 documents from the WOS Core Collection database that are pertinent to this study. It identifies positive phenomena in the collaboration between the two countries' academic communities and suggests enhancing cooperation in the field of renewable energy research by partially examining the cooperation between Chinese and German academic communities from the perspective of Chinese scholars. There are an infinite number of opportunities and potential for future collaboration between China and Germany in the renewable energy research field. The increasing collaboration between the academic communities of China and Germany in the field of renewable energy research will serve as a critical factor in the promotion of global sustainable development, thereby establishing a more sustainable, healthier, and environmentally friendly world for future generations.

Data availability

All data were obtained from the web of science database, and the data acquisition process is documented in this paper.

CRediT authorship contribution statement

Haiyang He: Writing – review & editing, Writing – original draft, Visualization, Software, Conceptualization. **Huazhong Tu:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Hongli Zhang:** Software, Methodology, Data curation. **Andi Luo:** Visualization, Validation, Resources. **Zheng Ma:** Project administration. **Xinmiao Yang:** Validation, Supervision, Formal analysis. **Yumeng Li:** Writing – review & editing. **Chunxue Yang:** Writing – review & editing, Software. **Jianhong Wang:** Software, Resources, Methodology. **Zhiling Zhao:** Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

References

[1] IPCC, Synthesis Report, Intergovernmental Panel on Climate Change, Cambridge, UK, 2007.
[2] German Bundestag. Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz–EEG) sowie zur Änderung des Energiewirtschaftsgesetzes und des Mineralölsteuergesetzes. G-SIG: 14019287. Available online: https://dip.bundestag.de/vorgang/gesetz-f%C3%BCr-den-vorrang-erneuerbarer-energien-erneuerbare-energien-gesetz-eeg-sowie/111957 (accessed on 10 March 2024).
[3] Organization for Security and Co-operation in Europe. Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply. Federal Ministry of Economics and Technology 3–26. Available online: https://www.osce.org/secretariat/101047 (accessed on 10 March 2024).
[4] Climate change laws of the world. Renewable energy sources Act (EEG) latest version - EEG 2022, Available online: https://climate-laws.org/document/renewable-energy-sources-act-eeg-latest-version-eeg-2022_1b40. (Accessed 10 March 2024).
[5] Susana Garrido Azevedo, Marcelo Santos, José Rodriguez Antón, Supply chain of renewable energy: a bibliometric review approach, Biomass Bioenergy 126 (2019) 70–83, https://doi.org/10.1016/j.biombioe.2019.04.022.
[6] Marques, Rogério Santos, Luís Oscar Silva Martins, Fabio Matos Fernandes, Marcelo Santana Silva, Francisco Gaudêncio Mendonça Freires, Wind power and competitiveness: a bibliometric analysis, Inf. Sociedade Estudos 30 (2) (2020).
[7] M.S. Reza, Musfika Mannan, Safat Bin Wali, M.A. Hannan, Ker Pin Jern, S.A. Rahman, K.M. Muttaqi, TM Indra Mahlia, Energy storage integration towards achieving grid decarbonization: a bibliometric analysis and future directions, J. Energy Storage 41 (2021) 102855, https://doi.org/10.1016/j.est.2021.102855.

[8] Omoseni Oyindamola Adepoju, Love Opeyemi David, Nnamdi Ikechi Nwulu, Analysing the impact of human capital on renewable energy penetration: a bibliometric reviews, Sustainability 14 (14) (2022) 8852, https://doi.org/10.3390/su14148852.
[9] Chien-Heng Chou, Sa Ly Ngo, Phung Phi Tran, Renewable energy integration for sustainable economic growth: insights and challenges via bibliometric analysis, Sustainability 15 (20) (2023) 15030, https://doi.org/10.3390/su152015030.
[10] Recep Ulucak, Ramazan Sari, Seyfettin Erdogan, Rui Alexandre Castanho, Bibliometric literature analysis of a multi-dimensional sustainable development issue: energy poverty, Sustainability 13 (17) (2021) 9780, https://doi.org/10.3390/su13179780.
[11] Melih Soner Celiktas, Tarkan Sevgili, Gunnur Kocar, A snapshot of renewable energy research in Turkey, Renew. Energy 34 (6) (2009) 1479–1486, https://doi.org/10.1016/j.renene.2008.10.021.
[12] Liliana N. Proskuryakova, Georgy V. Ermolenko, The future of Russia's renewable energy sector: trends, scenarios and policies, Renew. Energy 143 (2019) 1670–1686, https://doi.org/10.1016/j.renene.2019.05.096.
[13] Paweł Kut, Katarzyna Pietrucha-Urbanik, Bibliometric analysis of renewable energy research on the example of the two European countries: insights, challenges, and future prospects, Energies 17 (1) (2024) 176, https://doi.org/10.3390/en17010176.
[14] Adam Sulich, Tomasz Zema, The green energy transition in Germany: a bibliometric study, Forum Scientiae Oeconomia 11 (2) (2023) 175–195.
[15] P. Yang, Urban expansion of Energiewende in Germany: a systematic bibliometric analysis and literature study, Energy, Sustainability and Society 12 (2022) 52, https://doi.org/10.1186/s13705-022-00373-1.
[16] da Silva, Gustavo Henrique Romeu, Andreas Nascimento, Christoph Daniel Baum, Mauro Hugo Mathias, Renewable energy potentials and roadmap in Brazil, Austria, and Germany, Energies 17 (6) (2024) 1482, https://doi.org/10.3390/en17061482.
[17] Masahiro Sugiyama, Jun Muto, Measuring policy analytical capacity in renewable energy policy: Germany-Japan-US comparison, Rev. Pol. Res. 41 (1) (2024) 184–209, https://doi.org/10.1111/ropr.12527.
[18] X. Kao, W. Wang, Q. Kao, J. Zhang, Visualization of energy-environment-economy system research characteristics and hotspots evolution trends based on CiteSpace, Environmental Research Communications 4 (2022) 055004, https://doi.org/10.1088/2515-7620/ac637f.
[19] Dejian Yu, Zeshui Xu, Witold Pedrycz, Bibliometric analysis of rough sets research, Appl. Soft Comput. 94 (2020) 106467, https://doi.org/10.1016/j.asoc.2020.106467.
[20] Dejian Yu, Zeshui Xu, Hamido Fujita, Bibliometric analysis on the evolution of applied intelligence, Appl. Intell. 49 (2019) 449–462, https://doi.org/10.1007/s10489-018-1278-z.
[21] Dejian Yu, Libo Sheng, Shunshun Shi, A retrospective analysis of Journal of Forecasting: from 1982 to 2019, J. Forecast. 42 (4) (2023) 1008–1035, https://doi.org/10.1002/for.2921.
[22] Yixia Chen, Mingwei Lin, Dan Zhuang, Wastewater treatment and emerging contaminants: bibliometric analysis, Chemosphere 297 (2022) 133932, https://doi.org/10.1016/j.chemosphere.2022.133932.
[23] Lili Zhang, Ling Jie, Mingwei Lin, Risk management research in East Asia: a bibliometric analysis, International Journal of Intelligent Computing and Cybernetics 16 (3) (2023) 574–594, https://doi.org/10.1108/IJICC-10-2022-0276.
[24] J. Li, Chaomei Chen, CiteSpace Scientific and Technical Text Mining and Visualization, third ed., Capital University of Economics and Business Press, Beijing, China, 2022, p. 2.
[25] Web of Science, Web of science core collection, Available online: https://clarivate.com/webofsciencegroup/solutions/web-of-science/. (Accessed 2 April 2024).
[26] Information Office of the State Council of China. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Available online: http://www.scio.gov.cn/ztk/xwfb/102/10/Document/1245854/1245854.htm (accessed on 10 March 2024).
[27] Die Clearingstelle EEG KWKG. Erneuerbare-Energien-Gesetz - 2009 (Übersicht). Available online: https://www.clearingstelle-eeg-kwkg.de/eeg2009 (accessed on 10 March 2024).
[28] Ministry of Commerce of China, Policy environment, major achievements and implications of renewable energy development in Germany, Available online: http://de.mofcom.gov.cn/article/ztdy/200912/20091206656298.shtmll. (Accessed 10 March 2024).
[29] German International Climate Initiative, Über die IKI, Available online: https://www.international-climate-initiative.com/ueber-die-iki/. (Accessed 10 March 2024).
[30] P.M. Maçaira, A.M. Tavares Thomé, F.L. Cyrino Oliveira, A.L. Carvalho Ferrer, Time series analysis with explanatory variables: a systematic literature review, Environ. Model. Softw. 107 (2018) 199–209, https://doi.org/10.1016/j.envsoft.2018.06.004.
[31] D.D.S. Price, A general theory of bibliometric and other cumulative advantage processes, J. Am. Soc. Inf. Sci. 27 (1976) 292–306, https://doi.org/10.1002/asi.4630270505.
[32] T. Couture, Y. Gagnon, An analysis of feed-in tariff remuneration models: implications for renewable energy investment, Energy Pol. 38 (2010) 955–965, https://doi.org/10.1016/j.enpol.2009.10.047.
[33] M. Frondel, N. Ritter, C.M. Schmidt, C. Vance, Economic impacts from the promotion of renewable energy technologies: the German experience, Energy Pol. 38 (2010) 4048–4056, https://doi.org/10.1016/j.enpol.2010.03.029.
[34] M. Kalkuhl, O. Edenhofer, K. Lessmann, Learning or lock-in: optimal technology policies to support mitigation, Resour. Energy Econ. 34 (2012) 1–23, https://doi.org/10.1016/j.reseneeco.2011.08.001.
[35] S. Jacobsson, A. Bergek, D. Finon, V. Lauber, C. Mitchell, D. Toke, A. Verbruggen, EU renewable energy support policy: faith or facts? Energy Pol. 37 (2009) 2143–2146, https://doi.org/10.1016/j.enpol.2009.02.043.
[36] G8, Hokkaido toyako summit leaders declaration, Available online: http://www.mofa.go.jp/policy/economy/summit/2008/doc/doc080714_en.html, 2008. (Accessed 10 March 2024).
[37] M. Meinshausen, N. Meinshausen, W. Hare, et al., Greenhouse-gas emission targets for limiting global warming to 2°C, Nature 458 (2009) 1158–1162, https://doi.org/10.1038/nature08017.
[38] IEA, Germany energy mix data, Available online: https://www.iea.org/countries/germany/energy-mix. (Accessed 10 March 2024).
[39] C.E. Hoicka, J. Lowitzsch, M.C. Brisbois, A. Kumar, L. Ramirez Camargo, Implementing a just renewable energy transition: policy advice for transposing the new European rules for renewable energy communities, Energy Pol. 156 (2021) 112435, https://doi.org/10.1016/j.enpol.2021.112435.
[40] J. Egerer, J. Rosellón, W.-P. Schill, Power system transformation toward renewables: an evaluation of regulatory approaches for network expansion, Energy J. 36 (2015) 105–128, https://doi.org/10.5547/01956574.36.4.jege.
[41] W. Fischer, J.-Fr Hake, W. Kuckshinrichs, T. Schröder, S. Venghaus, German energy policy and the way to sustainability: five controversial issues in the debate on the "Energiewende", Energy 115 (2016) 1580–1591, https://doi.org/10.1016/j.energy.2016.05.069.
[42] B.P. Gabster, K. Van Daalen, R. Dhatt, M. Barry, Challenges for the female academic during the COVID-19 pandemic, Lancet 395 (2020) 1968–1970, https://doi.org/10.1016/S0140-6736(20)31412-4.
[43] C. Suart, K. Neuman, R. Truant, The impact of the COVID-19 pandemic on perceived publication pressure among academic researchers in Canada, PLoS One 17 (2022) e0269743, https://doi.org/10.1371/journal.pone.0269743.
[44] C. Suart, T. Nowlan Suart, K. Graham, R. Truant, When the labs closed: graduate students' and postdoctoral fellows' experiences of disrupted research during the COVID-19 pandemic, Facets 6 (2021) 966–997, https://doi.org/10.1139/facets-2020-0077.
[45] Meihui Zhong, Mingwei Lin, Bibliometric analysis for economy in COVID-19 pandemic, Heliyon 8 (9) (2022) e10757, https://doi.org/10.1016/j.heliyon.2022.e10757.
[46] I. Karakislak, N. Schneider, The mayor said so? The impact of local political figures and social norms on local responses to wind energy projects, Energy Pol. 176 (2023) 113509, https://doi.org/10.1016/j.enpol.2023.113509.
[47] The New Yorker, The obscene energy demands of AI, Available online: https://www.newyorker.com/news/daily-comment/the-obscene-energy-demands-of-ai. (Accessed 10 March 2024).
[48] Vries de, The growing energy footprint of artificial intelligence, Joule 7 (2023) 2191–2194, https://doi.org/10.1016/j.joule.2023.09.004.

[49] A. Kopka, N. Grashof, Artificial intelligence: catalyst or barrier on the path to sustainability? Technol. Forecast. Soc. Change 175 (2022) 121318 https://doi.org/10.1016/j.techfore.2021.121318.
[50] Masahiro Suzuki, Jessica Jewell, Aleh Cherp, Have climate policies accelerated energy transitions? Historical evolution of electricity mix in the G7 and the EU compared to net-zero targets, Energy Res. Social Sci. 106 (2023) 103281, https://doi.org/10.1016/j.erss.2023.103281.
[51] Jörg Radtke, Nino S. Bohn, Mind the gap: community member perceptions of shortcomings in diversity and inclusivity of local energy projects in Germany, Util. Pol. 85 (2023) 101686, https://doi.org/10.1016/j.jup.2023.101686.
[52] Jessica Weber, Coordination challenges in wind energy development: lessons from cross-case positive planning approaches to avoid multi-level governance 'free-riding, Land 12 (11) (2023) 1964, https://doi.org/10.3390/land12111964.
[53] C.N. Gonzalez-Brambila, L. Reyes-Gonzalez, F. Veloso, M.A. Perez-Angón, The scientific impact of developing nations, PLoS One 11 (2016) e0151328, https://doi.org/10.1371/journal.pone.0151328.
[54] Y. Pan, F. Dong, Dynamic evolution and driving factors of new energy development: fresh evidence from China, Technol. Forecast. Soc. Change 176 (2022) 121475, https://doi.org/10.1016/j.techfore.2022.121475.
[55] C. Zou, B. Xiong, D. Huaqing, D. Zheng, G. Zhixin, Y. Wang, L. Jiang, S. Pan, S. Wu, The role of new energy in carbon neutral, Petrol. Explor. Dev. 48 (2021) 480–491, https://doi.org/10.1016/S1876-3804(21)60039-3.
[56] Z. Wang, X. Li, X. Xue, Y. Liu, More government subsidies, more green innovation? The evidence from Chinese new energy vehicle enterprises, Renew. Energy 197 (2022) 11–21, https://doi.org/10.1016/j.renene.2022.07.086.
[57] X. Li, Y. Peng, Q. He, H. He, S. Xue, Development of new-energy vehicles under the carbon peaking and carbon neutrality strategy in China, Sustainability 15 (2023) 7725, https://doi.org/10.3390/su15097725.
[58] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. 24 (2019) 38–50, https://doi.org/10.1016/j.esr.2019.01.006.
[59] Z.P. Cano, D. Banham, S. Ye, A. Hintennach, J. Lu, M. Fowler, Z. Chen, Batteries and fuel cells for emerging electric vehicle markets, Nat. Energy 3 (2018) 279–289, https://doi.org/10.1038/s41560-018-0108-1.
[60] N. Kittner, F. Lill, D.M. Kammen, Energy storage deployment and innovation for the clean energy transition, Nat. Energy 2 (2017).
[61] G. Glenk, S. Reichelstein, Economics of converting renewable power to hydrogen, Nat. Energy 4 (2019) 216–222, https://doi.org/10.1038/s41560-019-0326-1.
[62] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, C. Weinhardt, Designing microgrid energy markets: a case study: the Brooklyn Microgrid, Appl. Energy 210 (2018) 870–880, https://doi.org/10.1016/j.apenergy.2017.06.054.
[63] J. Köhler, F.W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, et al., An agenda for sustainability transitions research: state of the art and future directions, Environ. Innov. Soc. Transit. 31 (2019) 1–32, https://doi.org/10.1016/j.eist.2019.01.004.
[64] A.V. Norström, C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, P. Balvanera, A.T. Bednarek, et al., Principles for knowledge co-production in sustainability research, Nat. Sustain. 3 (2020) 182–190, https://doi.org/10.1038/s41893-019-0448-2.
[65] P. Schroeder, K. Anggraeni, U. Weber, The relevance of circular economy practices to the sustainable development goals, J. Ind. Ecol. 23 (2019) 77–95, https://doi.org/10.1111/jiec.12732.
[66] K.S. Rogge, K. Reichardt, Policy mixes for sustainability transitions: an extended concept and framework for analysis, Res. Pol. 45 (2016) 1620–1635, https://doi.org/10.1016/j.respol.2016.04.004.
[67] F.W. Geels, F. Kern, G. Fuchs, N. Hinderer, G. Kungl, J. Mylan, M. Neukirch, S. Wassermann, The enactment of socio-technical transition pathways: a reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014), Res. Pol. 45 (2016) 896–913, https://doi.org/10.1016/j.respol.2016.01.015.
[68] C. Sheng, Y. Cao, B. Xue, Residential energy sustainability in China and Germany: the impact of national energy policy system, Sustainability 10 (2018) 4535, https://doi.org/10.3390/su10124535.
[69] N. Bezak, M. Mikoš, P. Borrelli, C. Alewell, P. Alvarez, J.A.A. Anache, J. Baartman, et al., Soil erosion modelling: a bibliometric analysis, Environ. Res. 197 (2021) 111087, https://doi.org/10.1016/j.envres.2021.111087.
[70] J.J. Frostad, Q.A.P. Nguyen, M.M. Baumann, B.F. Blacker, L.B. Marczak, A. Deshpande, K.E. Wiens, et al., Mapping development and health effects of cooking with solid fuels in low-income and middle-income countries, 2000–18: a geospatial modelling study, Lancet Global Health 10 (2022) e1395–e1411, https://doi.org/10.1016/S2214-109X(22)00332-1.
[71] P. Meyfroidt, A. De Bremond, C.M. Ryan, E. Archer, R. Aspinall, A. Chhabra, G. Camara, et al., Ten facts about land systems for sustainability, Proc. Natl. Acad. Sci. USA 119 (2022) e2109217118, https://doi.org/10.1073/pnas.2109217118.
[72] S. Oppel, M. Bolton, A.P.B. Carneiro, M.P. Dias, J.A. Green, J.F. Masello, R.A. Phillips, et al., Spatial scales of marine conservation management for breeding seabirds, Mar. Pol. 98 (2018) 37–46, https://doi.org/10.1016/j.marpol.2018.08.024.
[73] H. Yang, S.-N. Lu, Y. Song, Z. Chen, X.-F. Wu, Copper-mediated [3+2] cycloaddition of trifluoroacetimidoyl chlorides and N-isocyanoiminotriphenylphosphorane for the synthesis of 3-trifluoromethyl-1,2,4-triazoles, Org. Chem. Front. 8 (2021) 5040–5044, https://doi.org/10.1039/D1QO00843A.
[74] S. Kerr, L. Watts, J. Colton, F. Conway, A. Hull, K. Johnson, S. Jude, et al., Establishing an agenda for social studies research in marine renewable energy, Energy Pol. 67 (2014) 694–702, https://doi.org/10.1016/j.enpol.2013.11.063.
[75] K. Kowalski, S. Stagl, R. Madlener, I. Omann, Sustainable energy futures: methodological challenges in combining scenarios and participatory multi-criteria analysis, Eur. J. Oper. Res. 197 (2009) 1063–1074, https://doi.org/10.1016/j.ejor.2007.12.049.
[76] P. Ruiz, W. Nijs, D. Tarvydas, A. Sgobbi, A. Zucker, R. Pilli, R. Jonsson, et al., ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials, Energy Strategy Rev. 26 (2019) 100379, https://doi.org/10.1016/j.esr.2019.100379.
[77] F. Creutzig, P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, R.C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, Nat. Energy 2 (2017) 1–9, https://doi.org/10.1038/nenergy.2017.140.
[78] F. Sensfuß, M. Ragwitz, M. Genoese, The merit-order effect: a detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany, Energy Pol. 36 (2008) 3086–3094, https://doi.org/10.1016/j.enpol.2008.03.035.
[79] R. McKenna, S. Pfenninger, H. Heinrichs, J. Schmidt, I. Staffell, C. Bauer, K. Gruber, et al., High-resolution large-scale onshore wind energy assessments: a review of potential definitions, methodologies and future research needs, Renew. Energy 182 (2022) 659–684, https://doi.org/10.1016/j.renene.2021.10.027.
[80] C. Herbes, V. Brummer, J. Rognli, S. Blazejewski, N. Gericke, Responding to policy change: new business models for renewable energy cooperatives–Barriers perceived by cooperatives' members, Energy Pol. 109 (2017) 82–95, https://doi.org/10.1016/j.enpol.2017.06.051.
[81] F. Ueckerdt, L. Hirth, G. Luderer, O. Edenhofer, System LCOE: what are the costs of variable renewables? Energy 63 (2013) 61–75, https://doi.org/10.1016/j.energy.2013.10.072.
[82] V. Bertsch, M. Hall, C. Weinhardt, W. Fichtner, Public acceptance and preferences related to renewable energy and grid expansion policy: empirical insights for Germany, Energy 114 (2016) 465–477, https://doi.org/10.1016/j.energy.2016.08.022.
[83] P. Ringler, D. Keles, W. Fichtner, Agent-based modelling and simulation of smart electricity grids and markets–a literature review, Renew. Sustain. Energy Rev. 57 (2016) 205–215, https://doi.org/10.1016/j.rser.2015.12.169.
[84] A. Purkus, E. Gawel, D. Thrän, Addressing uncertainty in decarbonisation policy mixes–Lessons learned from German and European bioenergy policy, Energy Res. Social Sci. 33 (2017) 82–94, https://doi.org/10.1016/j.erss.2017.09.020.
[85] Y. Li, Q. Du, J. Zhang, Y. Jiang, J. Zhou, Z. Ye, Visualizing the intellectual landscape and evolution of transportation system resilience: a bibliometric analysis in CiteSpace, Dev. Built Environ. 14 (2023) 100149, https://doi.org/10.1016/j.dibe.2023.100149.
[86] Z. Shen, W. Ji, S. Yu, G. Cheng, Q. Yuan, Z. Han, H. Liu, T. Yang, Mapping the knowledge of traffic collision Reconstruction: a scientometric analysis in CiteSpace, VOSviewer, and SciMAT, Sci. Justice 63 (2023) 19–37, https://doi.org/10.1016/j.scijus.2022.10.005.

[87] J. Marquardt, Central-local relations and renewable energy policy implementation in a developing country, Environmental Policy and Governance 27 (2017) 229–243, https://doi.org/10.1002/eet.1756.
[88] A. Zerrahn, W.-P. Schill, C. Kemfert, On the economics of electrical storage for variable renewable energy sources, Eur. Econ. Rev. 108 (2018) 259–279, https://doi.org/10.1016/j.euroecorev.2018.07.004.
[89] W. Leal Filho, A. Lange Salvia, A. Do Paço, R. Anholon, O.L. Gonçalves Quelhas, I.S. Rampasso, A. Ng, A.-L. Balogun, B. Kondev, L.L. Brandli, A comparative study of approaches towards energy efficiency and renewable energy use at higher education institutions, J. Clean. Prod. 237 (2019) 117728, https://doi.org/10.1016/j.jclepro.2019.117728.
[90] R.J. Brecha, K. Schoenenberger, M. Ashtine, R. Koon Koon, Ocean thermal energy conversion—flexible enabling technology for variable renewable energy integration in the Caribbean, Energies 14 (2021) 2192, https://doi.org/10.3390/en14082192.
[91] Y. Li, A. Oberheitmann, Challenges of rapid economic growth in China: reconciling sustainable energy use, environmental stewardship and social development, Energy Pol. 37 (2009) 1412–1422, https://doi.org/10.1016/j.enpol.2008.12.002.
[92] V.G. Azevedo, S. Sartori, L.M.S. Campos, CO2 emissions: a quantitative analysis among the BRICS nations, Renew. Sustain. Energy Rev. 81 (2018) 107–115, https://doi.org/10.1016/j.rser.2017.07.027.
[93] Q. Zhang, H. Liao, Y. Hao, Does one path fit all? An empirical study on the relationship between energy consumption and economic development for individual Chinese provinces, Energy 150 (2018) 527–543, https://doi.org/10.1016/j.energy.2018.02.106.
[94] I.A. Jumare, R. Bhandari, A. Zerga, Environmental life cycle assessment of grid-integrated hybrid renewable energy systems in Northern Nigeria, Sustainability 11 (2019) 5889, https://doi.org/10.3390/su11215889.
[95] H. Marx, S. Forin, M. Finkbeiner, Organizational life cycle assessment of a service providing SME for renewable energy projects (PV and wind) in the United Kingdom, Sustainability 12 (2020) 4475, https://doi.org/10.3390/su12114475.
[96] B. Xue, Z. Ma, Y. Geng, P. Heck, W. Ren, M. Tobias, A. Maas, P. Jiang, J.A.P. de Oliveira, T. Fujita, A life cycle co-benefits assessment of wind power in China, Renew. Sustain. Energy Rev. 41 (2015) 338–346, https://doi.org/10.1016/j.rser.2014.08.056.
[97] W. McDowall, B.S. Rodriguez, A. Usubiaga, J.A. Fernández, Is the optimal decarbonization pathway influenced by indirect emissions? Incorporating indirect life-cycle carbon dioxide emissions into a European TIMES model, J. Clean. Prod. 170 (2018) 260–268, https://doi.org/10.1016/j.jclepro.2017.09.132.
[98] Climate Change Laws of the World, Federal climate protection Act, Available online: https://climate-laws.org/document/federal-climate-protection-act-and-to-change-further-regulations-bundesklimaschutzgesetz-or-ksg_c1c2. (Accessed 10 March 2024).
[99] Lili Zhang, Ling Jie, Mingwei Lin, Carbon neutrality: a comprehensive bibliometric analysis, Environ. Sci. Pollut. Control Ser. 30 (16) (2023) 45498–45514, https://doi.org/10.1007/s11356-023-25797-w.
[100] Thilo Wiertz, Lilith Kuhn, Annika Mattissek, A turn to geopolitics: shifts in the German energy transition discourse in light of Russia's war against Ukraine, Energy Res. Social Sci. 98 (2023) 103036, https://doi.org/10.1016/j.erss.2023.103036.
[101] Erik Hille, Europe's energy crisis: are geopolitical risks in source countries of fossil fuels accelerating the transition to renewable energy? Energy Econ. 127 (2023) 107061 https://doi.org/10.1016/j.eneco.2023.107061.
[102] Lili Zhang, Ling Jie, Mingwei Lin, Artificial intelligence in renewable energy: a comprehensive bibliometric analysis, Energy Rep. 8 (2022) 14072–14088, https://doi.org/10.1016/j.egyr.2022.10.347.
[103] M.B. Lindberg, The EU emissions trading system and renewable energy policies: friends or foes in the European policy mix? Polit. Govern. 7 (2019) 105–123, https://doi.org/10.17645/pag.v7i1.1800.