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Review

Two decades of nuclear energy policy and its impact on Indonesia: A bibliometric review

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Abstract: Although much bibliometric research has been conducted to analyze publications on energy policy, a systematic investigation of the sustainability of nuclear energy use after the Fukushima nuclear accident is still lacking. Therefore, this study conducted a comprehensive bibliometric review of the sustainability of nuclear energy policy (NEP). This study discusses NEPs, highlighting their disadvantages; emerging research themes; and networks of the most productive authors, countries, journals, and institutions over the last 20 years (2002–2022). This timeframe was selected because of the Fukushima nuclear accident, which has been one of the largest environmental disasters in recent years. Bibliometric analysis was carried out by reviewing 1146 documents from the Scopus database using the keywords "energy policy" and "nuclear energy." The OpenRefine software was used to deep-clean keywords with the same meaning, and VOSviewer was used to visualize them. The results show that over the past two decades, future research themes and trends in the study of NEP have focused on nuclear fuel, the Fukushima nuclear accident, risk perception, energy transition, and renewable energy. Bibliometric analysis has positively affected the development of NEP in countries that do not yet have nuclear power plants, such as Indonesia.

Keywords: nuclear energy policy; nuclear energy; Fukushima accident; bibliometric analysis; Indonesia

1. Introduction

Each country is working toward meeting the net zero emission (NZE) targets set in the Paris Agreement to combat climate change. Climate change is currently in the spotlight of many countries around the world, as it can cause huge social and economic losses. Nuclear energy is the right choice for achieving NZE targets owing to its advantages over wind, solar, and other renewable energy sources, such as low carbon emissions, fewer air pollutants, and higher energy density (Xia et al., 2019a). Nuclear energy is reliable, competitive, and sustainable. Thus, it is not surprising that many countries have chosen to use nuclear energy to meet their energy security requirements (Wang et al., 2018). Nuclear technology satisfies 17% of the world's electricity demand, and over 30 countries operate nuclear power plants (NPPs) (Erdoğan and Kaya, 2016). However, the public perception of nuclear energy has focused on the risks of nuclear accidents, radioactive waste, nuclear weapons, and high operating costs instead of its potential benefits. Perspectives play an important role in shaping public acceptance of nuclear energy and encouraging individuals to focus on solutions to environmental problems, which are associated with perceptions of the importance of energy policy (Wang et al., 2020).

The energy policies of each country, particularly those related to nuclear energy, can change as quickly as the events that follow. For example, after the Three Mile Island disaster in 1979, the Swedish Parliament ruled that nuclear power should be phased out by 2010. Since then, Sweden's NEP has gradually replaced nuclear power with renewable energy sources (Nohrstedt, 2005). As of 2007, 10 nuclear reactors were still operating in Sweden (Hedberg and Holmberg, 2008). Similarly, after the Fukushima nuclear accident, the US halted preconstruction work on two planned reactors. The new US security requirements have raised investor concerns regarding higher costs of nuclear power generation. However, the US government has reaffirmed its commitment to expand nuclear power as part of its clean energy policy (Holt, 2014). The emphasis on reactor safety has also increased since the Fukushima nuclear accident, which could extend the approval time for establishing future reactors to ensure compliance with design regulations (Heffron, 2013).

The aforementioned nuclear accidents exemplify how countries respond to and formulate their post-accident energy policies. Although a significant amount of bibliometric research has been conducted to analyze publications on energy policy, systematic attention on the sustainability of nuclear energy use after the Fukushima nuclear accident has received little attention. This study conducted a comprehensive bibliometric review of NEP sustainability. This study focuses on NEP, highlighting its disadvantages and emerging research themes, and provides an overview of the most productive authors, countries, journals, and institutions over the last 20 years (2002–2022) based on a bibliometric analysis. This timeframe was chosen because of the Fukushima nuclear accident, which has been one of the largest environmental disasters in recent years. The accident is referred to as a "great accident" by the International Atomic Energy Agency (IAEA) and the International Nuclear and Radiological Event Scale (INES) (Steinhauser et al., 2014). There are three main issues addressed in this study:

1) Bibliometric analysis provides a comprehensive understanding of current research topics on NEP, identifies research gaps, and generates ideas for future research.
2) This study provides an unprecedented overview of the development of global NEP research, particularly after the Fukushima nuclear accident.
3) NEP readiness in Indonesia is expected to be a model for developing countries in making decisions to utilize NPPs.

This study uses Scopus database, because the coverage of Scopus journals is larger in all fields compared to Web of Science (WoS) (Aghaei Chadegani et al., 2013; Mongeon and Paul-Hus, 2016). This bibliometric review of the Scopus database yielded several important contributions based on the aforementioned three primary concerns. First, we identify the authors whose publications can serve as benchmarks for future researchers, the geographic scope, and the most relevant journals on NEP. Second, we identify the most prominent NEP-related research themes over the past 20 years. These themes may become future research trends that may interest other researchers as novel prospective topics. Finally, to implement the results of the content analysis of NEPs and their impact on developing countries, the specific case of

Indonesia's NEP is discussed. Indonesia's NEP is a fascinating study because, despite not having any NPPs, Indonesia has had all the regulatory and policy frameworks necessary to "go nuclear" over the past four decades. Preparedness is expected to be a model for developing countries when deciding whether to build NPPs.

2. Materials and methods

2.1. Data collection

The Scopus database was used to obtain necessary documents via keyword analysis. Document evaluation was conducted in three stages, as shown in **Figure 1**. Stage 1 was the data collection stage in which search criteria were used to identify documents in the Scopus database. Scopus is a comprehensive database for bibliometric analysis containing information on documents published in indexed journals in several fields of knowledge. This database is widely used for bibliometric analysis. For more than 40 years, the Thomson Reuters WoS database was the only database that enabled such bibliometric studies. However, in November 2004, Elsevier Science launched Scopus, which quickly became a major competitor of WoS for scientific databases (Sánchez et al., 2017). Based on a literature search, the keywords that matched the research objectives were "energy policy" and "nuclear energy. The keyword selection was based on issues affecting NEPs over the last 20 years, particularly after the Fukushima nuclear reactor accident. A search of the Scopus database using these keywords yielded 1,146 documents on NEPs published in the last two decades. The selected data types included articles, conference papers, reviews, books, chapters, short surveys, and letters. Data filtering was performed to select English-language documents from 2002 to 2022. This timeframe included post-Fukushima energy policies in 2011. A data search was conducted on 16 August, 2022.

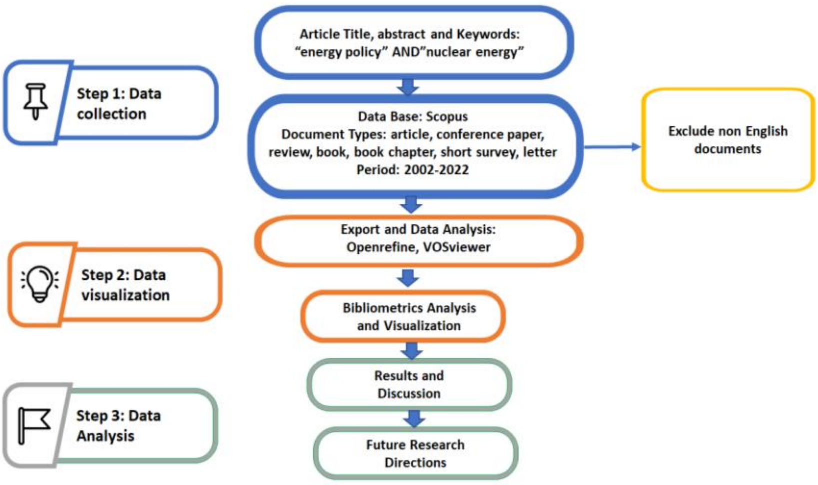

Figure 1. Main stages of the methodology and procedures used in this study.

2.2. Data visualizations

Stage 2 was the document-data visualization stage. Documents retrieved from the Scopus database were filtered based on the set criteria and downloaded as comma separated value (CSV) files. CSV is the simplest and most popular analytical format, offering flexible processing and two-dimensional data representation (Mahmud et al., 2018). The data were input into the OpenRefine web-based application for keyword cleanup (eliminating keywords with the same meaning). OpenRefine works with messy data by cleaning them, converting them from one format to another, expanding them with web services, and linking them to other databases (Larsson, 2013). Following keyword cleanup, words with the same meaning must be re-cleaned by manually applying a thesaurus to a text file. The results of the cleaned data were exported back into CSV format and input into the VOSviewer software. VOSviewer, a freely available tool designed to facilitate the creation and viewing of bibliometric maps (van Eck and Waltman, 2009), is increasingly being recognized and utilized for bibliometric research (Aleksandra Kuzior, 2022). VOSviewer was selected because of its ease of use and flexibility, which substantially reduces opportunity costs for new users (Kirby, 2023). VOSviewer can create maps of authors or journals based on co-citation data and keyword maps based on co-occurrence data. Thus, VOSviewer can display network maps of authors, countries, keywords, citations, and scientific journals.

2.3. Data analysis

Stage 3 was the data analysis stage to identify the main themes discussed in NEP-related research. The output was displayed as interrelated circles to illustrate the existing relationships. Different colors represented clusters and different terms. The number of clusters in each network map varied depending on the number of links.

3. Results

3.1. Number of publications

Searches of the Scopus database showed that 1146 studies on NEPs have been published between 2002 and 2022. The number of publications increased during the period under investigation, as shown in **Figure 2**. Between 2002 and 2012, there were fluctuations and a tendency toward stagnant growth with regard to the number of NEP-related publications. After the Fukushima accident, this number gradually increased from 2012 to 2020, and sharply increased from 2020 to 2021. The trend showed a decrease in 2022 because data gathering took place in the middle of the year.

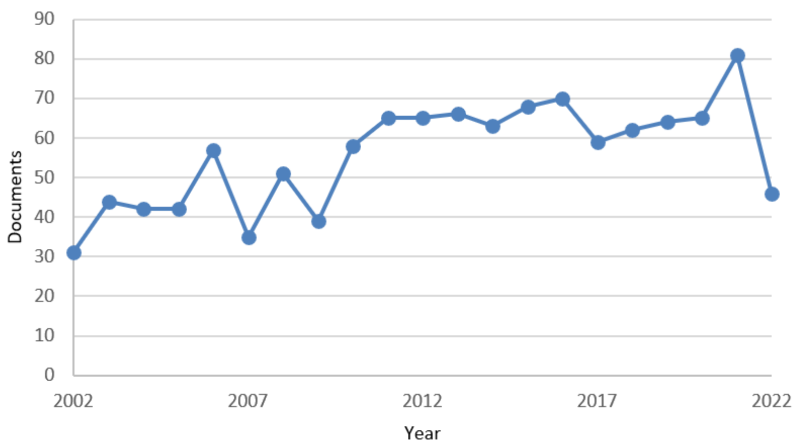

Figure 2. Distribution of the number of publications between 2002 and 2022.

3.2. Leading authors and citations

Leading authors, citations, countries, journals, and organizations are essential to bibliometric analysis because they provide valuable insights into the impact and relevance of research produced by authors, countries, journals, or organizations with well-established reputations in NEP research.

This section analyzes the most frequently cited publications. Citation analysis evaluates the citation relationship between two published documents, resulting in a quality assessment of the publication based on the number of times it has been cited. VOSviewer maps the minimum number of publications specified by the same source to be included in the criteria.

On the 1146 authors of NEP-related publications, only one was credited in seven documents (BK Sovacool). **Figure 3** shows the top 14 authors based on the number of citations and documents. One of the most popular authors was W. Poortinga, with 814 citations and 5 documents, followed by B.K. Sovacool and N.F. Pidgeon. Poortinga conducted research on environmental risk perception, sustainability, behavior, and lifestyle. Among the top 14 authors, 3 were from the UK and 2 were from the same institution (Cardiff University).

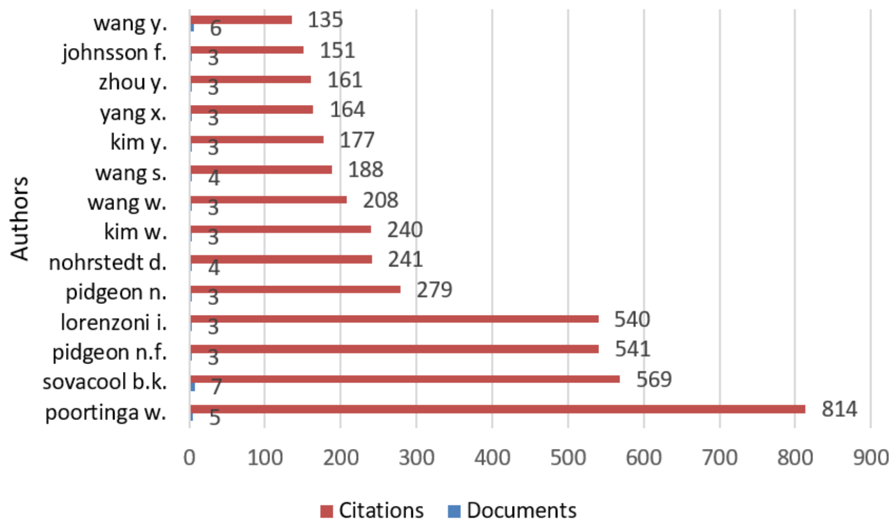

Figure 3. Distribution of the top 14 authors based on the number of citations and documents.

3.3. Leading countries

By analyzing leading countries, one can evaluate a country's scientific and technological superiority and observe its collaboration patterns, such as whether it collaborates exclusively with developed countries or has networks with developing countries.

Table 1 lists the number of citations of the documents published in each country. The US had the biggest number of publications on NEP with 188 documents (10.29%), followed by the UK (116 documents, 10.12%) and China (98 documents, 8.37%).

Table 1 shows the 20 countries on the co-authorship visualization map with country analysis units. The database input into VOSviewer identified the top 20 countries based on the number of documents and citations after filtering on the desired data threshold. The US leads in NEP formulation. Just a day after the Fukushima incident, the US was put on alert because the incident had the potential to disrupt efforts to promote nuclear power for reducing global warming (Steding, 2011).

Table 1. Number of citations based on the number of documents published by a country.

Country/Territory	Documents	Citations
United States	188	4069
United Kingdom	116	2925
China	98	1903
Japan	91	1136
South Korea	76	1245
Germany	60	1190
Turkey	41	809
Australia	39	700
France	36	394
Poland	32	226
India	26	607
Taiwan	24	344
Netherlands	22	446
Sweden	22	640
Finland	21	582
Italy	20	292
Austria	19	360
Spain	18	285
Switzerland	18	541
Canada	16	225

Figure 4 shows the collaboration between researchers based on country; six distinct clusters were identified. Links and lines indicate the significance of publications cited by countries. The illustration indicates that the cooperation between the developed and developing countries has existed for several years. The United States (blue), United Kingdom (red), Japan (green), India (yellow), Germany (purple), and Poland (light blue) stand out in the six clusters. Studies on NEP in China and South Korea do not stand out than in the US and UK, as it was only in 2021 that the Chinese government announced it would achieve the goal of carbon neutrality by 2060 (Jia and Lin, 2021) and approved plans to phase out coal-fired power plants and increase the share of non-fossil fuels to around 20% by 2030 (Zhou et al., 2019). Meanwhile, in South Korea, starting in 2018, there is a downward trend in the use of nuclear energy until only 10 nuclear reactors are operating in 2037 (Kim and Jeon, 2020).

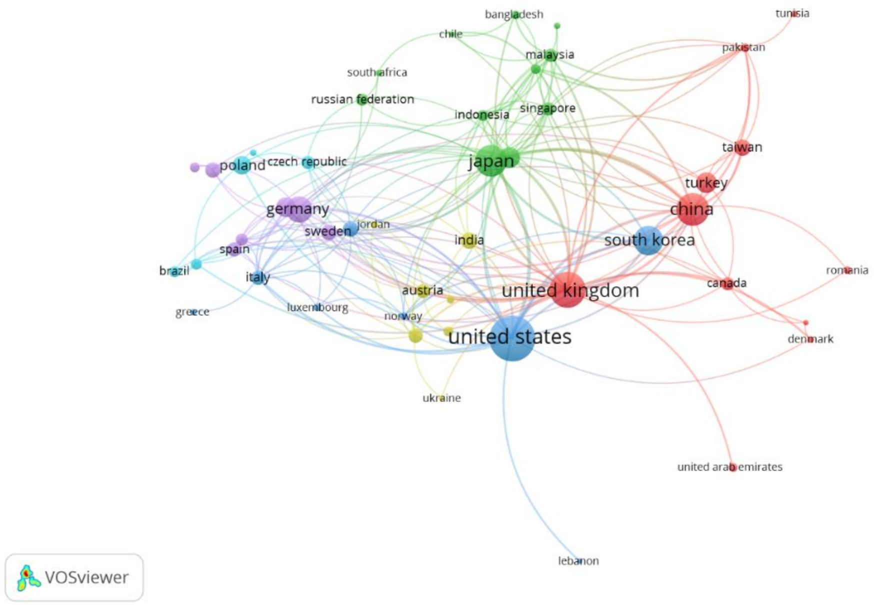

Figure 4. Network visualization of co-authorship of NEP studies by country.

3.4. Leading journals

An analysis of leading journals can be used to determine the extent to which high-quality journal-published research reaches readers. **Figure 5** shows the sources of NEP-related articles in VOSviewer from 2002 to 2022. To obtain the top 20 sources, the minimum number of publications and citations was set to 3 and 91, respectively. Journal linkages with citations were observed based on the distance and line thickness of each journal on the visualization map. **Figure 5** and **Table 2** show that the most frequently cited journal was Energy Policy (166 documents, 7627 citations), followed by Energy (30 documents, 1239 citations) and Energies (28 documents, 261 citations). **Figure 5** shows 3 clusters of frequently cited journals. In the red cluster, the biggest node is Energy Policy, followed by Renewable and Sustainable Energy Reviews and International Journal of Global Energy Issues, indicating that the review journals have a wider impact. The connecting line between Energy Policy and Renewable and Sustainable Energy Reviews is thicker than the other lines in the red cluster, meaning that these two journals have higher co-citation strength with each other. In the blue cluster, the journals with the biggest nodes are Progress in Nuclear Energy and Applied Energy. Both journals have a strong co-citation relationship with Energy Policy. The green cluster includes Energy, Energies, and Energy and Environment which also have a strong co-citation relationship with Energy Policy. This cluster analysis shows that Energy Policy influences almost all NEP-related journals. **Table 2** shows that the number of documents was proportional to the number of citations. These journals were the most productive over the last 20 years.

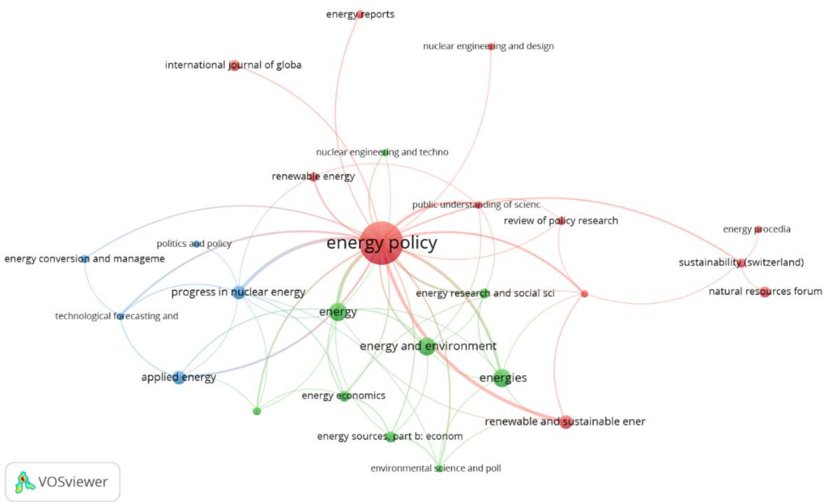

Figure 5. Journal network visualization based on total link strength.

Table 2. Top 20 journals with the most documents and citations.

Journals	Documents	Citations
Energy Policy	166	7627
Energy	30	1239
Energies	28	261
Energy and Environment	28	143
Nuclear Engineering International	22	5
Nuclear News	18	4
Progress in Nuclear Energy	17	313
Applied Energy	16	525
Renewable and Sustainable Energy Reviews	16	776
Energy Sources, Part B: Economics, Planning, And Policy	11	105
Energy Economics	10	355
International Journal of Global Energy Issues	10	41
Natural Resources Forum	10	158
Energy Research and Social Science	9	182
International Conference on Nuclear Engineering, Proceedings, Icone	9	12
IOP Conference Series: Earth and Environmental Science	9	4
Sustainability (Switzerland)	8	48
Petroleum Review	7	0
Renewable Energy	7	183
Energy Conversion and Management	6	339

3.5. Leading organizations

An analysis of leading organizations seeks to evaluate the contribution of organizations (universities or research institutions) in supporting high-impact research. It can be used to identify trends in collaboration among organizations.

Table 3. Organizations that contribute to NEP-related research.

Organization	Documents	Citations
Center of International Security and Studies at Maryland, School of Public Policy, University of Maryland, 4113 Vans Munching Hall, MD 20742, United States	3	161
Energy Studies Institute, National University of Singapore, Singapore	3	79
Graduate School of Energy Science, Kyoto University, Yoshida Hamachi, Tokyo-Ku, Kyoto, 606-8501, Japan	3	31
Inet, Tsinghua University, Beijing, 100084, China	3	29
Silesian University of Technology, Poland	3	26
Silesian University of Technology, Institute of Thermal Technology, Gliwice, Poland	3	25
Department of Agricultural and Environmental Chemistry, University of Life Sciences in Lublin, 15 Akademicka Street, Lublin, 20-950, Poland	3	3
Department of EEE, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh	3	2
University Politehnica of Bucharest, Romania	3	2

Table 3 lists the top 9 organizations that contributed to NEP-related research since 2002. These nine organizations have the same number of documents, i.e., three documents. The Center of International Security and Studies in Maryland had the highest number of citations (161).

3.6. Keyword network

To confirm the topics and fundamental issues in NEP-related research, it is crucial to examine each document and extract the most essential keywords. This analysis is essential for determining trends in emergent themes and identifying potential hotspots for research, development, and innovation. **Figure 6** shows four clusters of different colors.

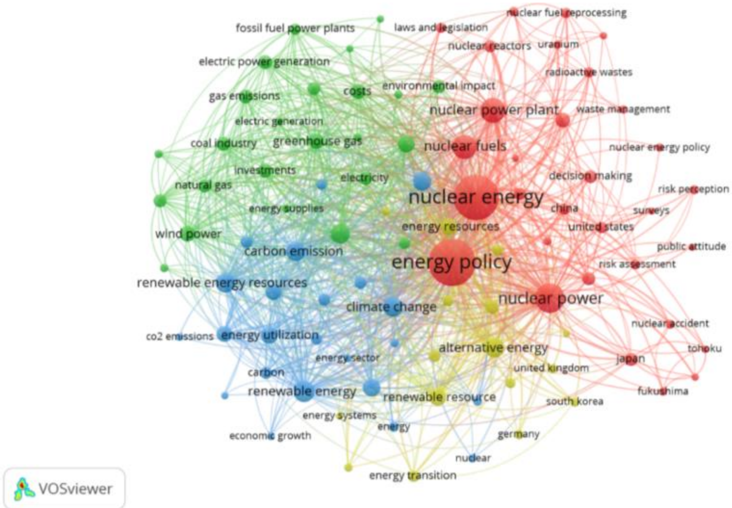

Figure 6. Network of keywords based on total link strength.

Each cluster indicates the most relevant sources identified by the keyword "energy policy" associated with "nuclear energy." It can be seen that a strong relationship exists among clusters. In this study, data filtering was performed using the VOSviewer application to examine the keyword "energy policy" associated with "nuclear energy" in the period 2002–2022. Based on the database input into

VOSviewer, there were 6473 keywords, with each keyword appearing at least 25 times with 98 related keywords. The data for these 98 keywords are shown in **Figure 6**, with four dominant clusters. The size of a circle represents the number of articles for each keyword, whereas the color represents the cluster in which the keywords appeared the most.

The cluster highlighted in green contains keywords related to energy sources, such as coal, wind, fossil fuels, and natural gas. The blue cluster contains keywords associated with renewable energy sources for addressing climate change. The yellow cluster contains keywords related to alternative energy and energy transition. The red cluster contains keywords related to nuclear energy and energy policy, such as nuclear fuel, nuclear accidents, Fukushima, and risk perception. In general, in the co-occurrence analysis of authors' keywords, the larger the size of the circle, the more often the keyword appears. **Figure 6** demonstrates that the fourth cluster is the most dominant, as indicated by its large hotspot size. This analysis is important for identifying trends in emerging themes and hotspots that could be of interest for further research, development, and innovation.

For the co-occurrence analysis, the relevant and recent publications were grouped into clusters. The research topics were based on research interests, number of publications found at the time of the literature search, and most relevant topics. In **Figure 7**, the color of each circle indicates the appearance of keywords corresponding to the year of publication. **Figure 7** illustrates that before the Fukushima nuclear accident in 2011, energy-related research concentrated on issues such as waste management, environmental effects, and energy sources such as coal, wind, fossil fuels, and natural gas. After the Fukushima accident, from 2011 to 2015, the focus areas expanded to include energy policies, nuclear energy, alternative energy sources, climate change, and Fukushima, Japan. From 2016 onward, studies have dealt with risk perception, nuclear accidents, renewable energy, transition energy, nuclear fuel, and the Fukushima accident. The findings of this study are reported in highly influential articles; therefore, the analysis of the emergence of these findings could indicate significant developments in NEP research. It would also be interesting to examine its popularity over the past 20 years.

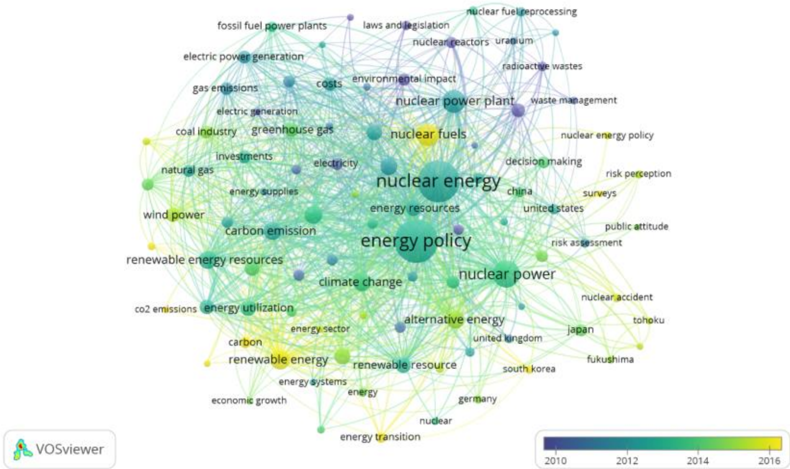

Figure 7. Keyword visualization overlay map.

4. Discussion

4.1. Research themes

Based on the cluster analysis in **Figure 6** and keyword visualization in **Figure 7**, the most recent themes in NEP research (shown with yellow hotspots in **Figure 7**) are nuclear fuel, the Fukushima nuclear accident, risk perception, energy transition, and renewable energy. This section analyzes the most prominent themes that represent each cluster.

4.1.1. Nuclear fuel

Nuclear fuel has become a topic of interest since the International Forum of Generation IV recognized Generation IV reactors as one of the six most promising nuclear reactor designs (Shafii et al., 2021) in terms of improved safety, sustainability, efficiency, and cost. This has driven continuous innovation, development, and design of fuels (Olander, 2009; Stan, 2009). In the long-term energy policy for nuclear energy, fast reactors are preferred because they allow for a more efficient use of nuclear fuel and ensure a supply of fissile materials (Locatelli et al., 2013). Energy efficiency is important because the average operating period of a nuclear reactor is 23 years, whereas the operation of existing reactors ends after an average of 40 years (Zittel et al., 2013). One interesting issue is the problem of spent fuel in NPPs. Radioactive waste must be safely managed to ensure that it does not endanger human health or the environment (Ratiko et al., 2020). According to the IAEA safety standards, radioactive waste must be stored in such a way that it can be monitored, inspected, recovered, and disposed of under conditions suitable for further management (International Atomic Energy Agency, 2009).

4.1.2. Fukushima nuclear accident

The earthquake and tsunami in Fukushima, Japan severely damaged the reactor core in three of the six nuclear reactors, releasing hydrogen and radioactive material. The accident resulted in the evacuation of the local population, huge economic losses, and closure of all NPPs in Japan. The Fukushima nuclear accident has had a profound impact on global security, the environment, and energy policy (Hayashi and Hughes, 2013; Steinhauser et al., 2014). The Fukushima nuclear disaster has revived international debate on the future of nuclear energy. The Fukushima accident has been used to justify NPPs and to reconsider past decisions regarding established or planned nuclear power sites (Wittneben, 2012).

In the UK, policymakers remained firm in their decision to increase the number of NPPs. The federal government in Germany temporarily shut down old nuclear reactors and re-examined all national nuclear security facilities (Wittneben, 2012). A British national survey found that attitudes toward nuclear energy remain divided, with only a small percentage of respondents declaring unconditional acceptance. In general, people who express concerns about climate change and energy security and have higher environmental values tend to reject nuclear power. Concerns regarding climate change and energy security are expected to increase the acceptance of nuclear energy under specific conditions, particularly when other options are less feasible (Corner et al., 2011).

The Chinese government has adopted several strategies to increase public acceptance of nuclear energy. For example, it encouraged people to take care of the environment by publicizing issues related to climate change and energy shortages. It has promoted the advantages of nuclear energy, such as low carbon emissions and high efficiency, as a solution to environmental problems (Boulton, 2018). It has also applied several strategies to increase public awareness of environmental issues, such as publishing policy documents and producing environmental protection propaganda online (F. Wang et al., 2020). However, the government should also provide information on nuclear safety, such as supplementing nuclear energy construction-related measures, improving emergency responses to nuclear accidents, increasing investments in nuclear energy technology, and increasing compensation under basic nuclear safety laws to protect the public (Xia et al., 2019b). Several countries responded differently to the nuclear disaster in Fukushima, particularly with regard to their NEPs. **Table 4** summarizes the NEPs of several countries before and after the Fukushima nuclear accident.

Table 4. NEP in several countries before and after the Fukushima nuclear accident.

Country	Before	After
Japan	• The Japanese government will reduce greenhouse gas emissions by 25 % (Kuramochi, 2015). Consequently, the growth of nuclear energy electricity capacity is projected to increase from 50 GW to 68 GW (Duffield, 2016). • Several nuclear accidents, such as JCO in 1999 and Kashiwazaki-Kariwa in 2007, have resulted in negative public attitudes toward nuclear energy (Aoyagi, 2021).	• The Japanese government revised its energy policy to reduce its reliance on nuclear power; before restarting, reactors were subjected to stress tests (Duffield, 2016). • In 2013, despite deficient energy self-sufficiency (4%), the Japanese government once again implemented a long-term nuclear phase-out policy (Shim et al., 2015).
South Korea	• The Korean government has implemented a fundamental plan to increase renewable energy use from 2.1% in 2003 to 7.7% in 2030 (Park and Ohm, 2014). The Korean government announced in 2010 its intention to export 80 nuclear reactors by 2030 (Shim et al., 2015).	• In 2016, the Korean government reaffirmed its commitment to nuclear energy and constructed six new reactors (Shim et al., 2015). In 2011, the Korean government established the Nuclear Safety and Security Commission as a new independent regulatory agency (Shim et al., 2015).
Germany	• The German government announced in 1998 its intention to phase out NPPs by 2022, but these plans were postponed in 2009 (Shim et al., 2015).	• The Fukushima accident provided the German government with the political cover to expedite the phase-out of nuclear energy (Srinivasan and Gopi Rethinaraj, 2013).
United Kingdom	• Nuclear power is viewed not only as a means to enhance energy security, but also as a pure energy source that will meet future energy demands and contribute to climate change mitigation (Poortinga et al., 2013).	• The UK appears unaffected by the Fukushima nuclear accident and intends to replace obsolete replace obsolete equipment and add new capacity (Srinivasan and Gopi Rethinaraj, 2013).
France	• France pursues nuclear development primarily to attain energy independence (Shim et al., 2015).	• Without significant policy changes, France is anticipated to maintain its commitment to nuclear energy (Srinivasan and Gopi Rethinaraj, 2013).
China	• Chinese government has encouraged people to take care of the environment by publicizing issues related to climate change and energy shortages (Wang et al., 2020).	• The Chinese government has also applied several strategies to increase public awareness of environmental issues, such as publishing policy documents and producing environmental protection propaganda online (Wang et al., 2020).
United States	• The 1979 disaster at Three Mile Island prompted a reduction in nuclear investment by the US government (Shim et al., 2015).	• The Fukushima accident had little effect on the future of nuclear energy in the US, with except for stricter safety regulations and delays in approving new nuclear power facilities (Srinivasan and Gopi Rethinaraj, 2013).

In Japan, the Fukushima nuclear accident was a turning point in the management of nuclear energy and its NEP. A major outcome of the accident was the loss of public confidence not only in relation to nuclear safety, but also in the country's energy policy as a whole. Even five years after the disaster, more than 80% of the Japanese people were in favor of stopping the use of nuclear power (Boulton, 2018). The Japanese government plans to reduce its reliance on nuclear energy while addressing five major problems: waste fuel management, management of plutonium deposits, radioactive waste disposal, human resource management, and restoration of public trust (Boulton, 2018). It intends to review the blueprint of NEP, prepare a new policy framework, and approve several new laws or amendments to encourage organizational, administrative, disaster risk management, and nuclear energy safety regulatory reform (Shadrina, 2012). After the Fukushima accident, the judiciary and local government institutions became more influential in the NEP formulation (Kikuchi, 2020). Furthermore, nuclear disasters have encouraged people to use electricity more efficiently (Iwai and Shishido, 2013). This is considered one of the driving forces in seeking alternative power sources (Komiyama and Fujii, 2017).

4.1.3. Risk perception for nuclear energy

Risk perception of nuclear energy is a subjective assessment made by people regarding the characteristics and severity of nuclear energy risks. The Fukushima nuclear accident severely influenced attitudes toward nuclear energy in many countries. Switzerland, for instance, has become increasingly aware of its use of nuclear energy. These findings suggest that the Fukushima accident triggered a change in public opinion; however, over time, public opinion on nuclear energy reverted to pre-accident levels (Kristiansen et al., 2018). In Taiwan, the risk perceptions of climate change, earthquakes, NPPs, and food security are positively correlated (Bian et al., 2021). A study on the risk perception of nuclear energy in China showed that environmental concerns and beliefs about an energy shortage are key determinants of the perception and public acceptance of nuclear energy (Hu et al., 2021). Public acceptance has shown consistency with China's nuclear development trends (Huang et al., 2018).

Public attitudes toward nuclear technology and facilities are among the key factors in South Korea's national energy and electricity policymaking process. The South Korean government and nuclear-related organizations actively reflect public attitudes and opinions toward national nuclear energy by promoting interactions between the government, organizations, and the public so that the resulting policies are reflected in South Korea's nuclear industry (Park, 2019). Trust in the government and perceived benefits are positive, whereas risk perception is negative and significant with regard to public acceptance of nuclear energy (Wang et al., 2020). Nuclear policymakers and practitioners should take steps to reverse public perceptions that the daily operation of an NPP could emit radiation that could damage the environment and health, and that the technology used in an NPP could be weaponized (Ho et al., 2018).

4.1.4. Energy transition

Energy transition is the process in which fossil fuels are replaced with low-carbon energy sources. Technological innovation is an important driving force in the energy transition (Hansen et al., 2019). In the US, smart grids offer the opportunity to implement energy transitions driven by government policies (Solomon and Krishna, 2011). Smart grids integrate information and communication technologies with energy networks (Camarinha-Matos, 2016; Wu and Tran, 2018). In Brazil, the energy transition to bioethanol has gained the support of stakeholders for large-scale promotions, thus expanding job creation and the support for national sugar producers (Solomon and Krishna, 2011). In the Netherlands, energy transition is being carried out by the government by identifying several problematic policies and forming a transition management model, although the transition to sustainable energy has yet to be fully addressed (Kern and Smith, 2008). In South Korea, the transition to a safer and more environment-friendly electricity system has reduced the reliance on coal and NPPs in favor of new and renewable energy sources (Kim, 2018). Given that global energy consumption has risen sharply owing to human population growth, improved living standards, and large-scale industrialization in developing countries (Yu et al., 2012), energy storage models are crucial to strengthening zero-carbon energy needs, such as renewable energy sources (Gallo et al., 2016). A case study of energy transition in Japan showed that a blockchain for energy transition with a holistic approach contributed to future digitalization, decentralization, and decarbonization (Ahl et al., 2020). The energy transition will be a benchmark in energy policy-making. The pressure to maintain affordability and energy security must be applied by continuously promoting the need to reduce carbon emissions. It has triggered a broad energy transition toward decarbonization, decentralization, and digitalization (Andoni et al., 2019). Nuclear energy is not only an energy transition solution but also a solution to climate change and global warming. Assessments by the Intergovernmental Panel on Climate Change confirmed that climate change has become a major threat to life-supporting systems (Verbruggen, 2008).

4.1.5. Renewable energy

Renewable energy is sustainable energy sourced from nature, such as solar power, wind power, water currents, biological processes, and geothermal energy. This theme has been discussed for a long time as countries seek to reduce greenhouse gas emissions associated with energy production to combat climate change (IRENA, 2018). Renewable energy can provide a sustainable supply of electricity and mitigate the negative impacts of fossil fuels on the environment (Tripathi et al., 2016). Renewable energy is the basis of strategies for sustainable energy development to save energy on the demand side, increase energy production efficiency, and replace fossil fuels with various renewable energy sources (Lund, 2007). Although the concept of renewable energy remains questionable (Harjanne and Korhonen, 2019), it has dominated energy policy-making at the national and international levels. Communities in the United States and Japan have shown increased acceptance of renewable energy sources and awareness of clean energy (Murakami et al., 2015). The increased use of renewable resources will contribute to economic growth and mitigate greenhouse gas emissions in a country (Can Şener et al., 2018). In public discourse, renewable energy is framed in such a way that it is strongly related to success in sustainability and climate change mitigation (Harjanne and Korhonen, 2019).

4.2. Future research directions

Future research on radioactive waste management and spent nuclear fuel (Wisnubroto et al., 2021), particularly in countries that plan to establish NPPs, poses a unique challenge. Despite its abundant potential, thorium fuel will determine the sustainability of the next-generation nuclear industry (Humphrey and Khandaker, 2018). Furthermore, research aimed at extending the fuel cycle, reducing radiotoxicity, improving the stability of spent fuel, and using mixed thorium–uranium nuclear fuels (van der Walt et al., 2023) will determine the design of future reactors.

Further research should explore safety improvements after the Fukushima accident. These include revising nuclear deterioration guidelines by incorporating health risks from a radiation protection perspective (Oka, 2022), strengthening the monitoring of radioactivity in food by several of Japan's neighboring countries (Kong et al., 2022), and reviewing political decision-making methods for environmental remediation (Takeuchi et al., 2021) to maintain safety standards and balance environmental and economic burdens.

After the Fukushima nuclear accident, research on the risk perception of nuclear energy has continued, particularly in Southeast Asian countries such as Indonesia (Abdullah et al., 2023; Wisnubroto et al., 2023), Malaysia, Singapore (Ho et al., 2022), Thailand (Vechgama et al., 2023), and the Philippines (Belmonte et al., 2023). These countries are expected to continue developing their nuclear energy.

Future research on the energy transition theme should examine how technologies for low-carbon energy transitions could affect social justice issues. In this context, the concept of "just transition" (Banerjee and Schuitema, 2022; Garvey et al., 2022; Upham et al., 2022; Wang and Lo, 2021) was introduced to draw attention to issues of equality and social justice in an effort to address energy and climate issues. These have been recognized as important components of the low-carbon energy transition.

As interest in the application and consumption of renewable energy worldwide continues to rise (Yolcan, 2023), future research should explore how renewable energy can contribute to providing sustainable energy. The more renewable energy is developed, the more effective it is in reducing environmental pressures in poor countries compared with rich countries (Li et al., 2023).

The aforementioned themes have frequently emerged in NEP research over the past 20 years and present a challenge for researchers to take advantage of the opportunities to formulate NEP.

4.3. Nuclear energy policy in Indonesia

According to the cluster analysis in **Figure 6** and the keyword visualization in **Figure 7**, the most recent themes in NEP research related to nuclear energy are nuclear fuel, the Fukushima nuclear accident, and risk perception. These themes can be the main reference in making NEPs, especially for developing countries that want to have NPPs as a new energy source, such as Indonesia. For more than 60 years, the National Nuclear Energy Agency has managed several nuclear facilities, such as radioactive waste management, nuclear fuel manufacturing, and radioisotope-radiopharmaceutical production, including research reactors in Bandung, Yogyakarta, and Serpong (Wisnubroto et al., 2023). The Indonesian government has been preparing the NPP development program for almost 40 years but has yet to make the decision to "go nuclear" (Wisnubroto et al., 2023). Through the National Research and Innovation Agency, the government issued a policy paper recommending the construction of NPPs by 2025 to meet the 35 GW energy demand target by 2060 (Alam, 2022). Indonesia's energy demand will continue to increase over a 10-year period from 40,575 GWe to 51,075 GWe to meet the NZE target by 2030. Furthermore, the government aims to increase electricity demand to 2500 kilowatt-hours (kWh) per capita by 2025 and 7000 kWh by 2050 (IEA, 2022). To meet NZE targets in line with the development of a green economy, such energy needs must be met using clean and sustainable energy sources, such as nuclear energy.

Technically, an NPP that can be built in Indonesia is a type of light-water reactor built on land by licensed operators with proven technology and operating permits. Proven technology will also increase the public acceptance of NPPs. Currently, Indonesia has two potential sites suitable for a comprehensive study: the Muria and Bangka sites. Other locations are also being studied, such as the West and East Kalimantan sites (Abdullah et al., 2023; Susiati et al., 2022). Concerns over nuclear fuel storage and nuclear waste management and public perceptions of nuclear energy, especially after the Fukushima nuclear accident, can be addressed, given that these two provinces have large areas with small populations.

The construction, operation, and decommissioning of an NPP must be consistent and must comply with laws and regulations. Compliance with the framework of International Nuclear Law is essential, as the development of an NPP could affect cross-border transit. The government has clearly expressed its desire to develop an NPP and its commitment to safety, security, and non-proliferation, as stated in relevant laws and government regulations, such as Law No. 10 of 1997 on Nuclear Disruption; Law No. 30 of 2007 on Energy; and Government Regulation No. 79 of 2014 on National Energy Policy. Indonesia ratified the Nuclear Non-Proliferation Treaty in 1978, marked by the promulgation of Act No. 8 of 1978 on the ratification of the Convention on the Prevention of the Proliferation of Nuclear Weapons.

To promote a culture of safety and security, the implementation of a management system for the development and operation of NPPs in Indonesia must comply with the relevant government regulations, including those of the Nuclear Energy Monitoring Agency (Bapeten) and IAEA safety standards. The IAEA safety standards associated with the radiation protection aspects of NPP design to protect humans and the environment have been adopted in the following government regulations: Law No. 26 of 2002 on Fuel Transportation; Law No. 27 of 2002 on Management of Radioactive Waste; and Regulation of the Head of Bapeten No. 4 of 2009 concerning the Decommissioning of Nuclear Reactors. Indonesia is a member of the IAEA Nuclear Security Guidance Committee and has actively contributed to the development of international guidelines and recommendations for nuclear security.

The impacts of construction, operation, and decommissioning of NPPs on the environment must be properly managed and monitored. Guidelines for the preparation of environmental impact analysis are issued by the Ministry of Environment and Forestry, while the guidance on the mechanism for environmental impact analysis of the construction and operation of nuclear reactors is regulated by Bapeten Chairman Regulation No. 03 of 2014 on the Analysis of Environmental Impacts for Nuclear Installations. Regarding the importance of radioactive waste management derived from research, the nuclear industry, including the operation and decommissioning of

NPPs, is regulated by Law No. 10 of 1997 in Nuclear Energy and Government Regulation No. 61 of 2013 on Management of Radioactive Waste.

Related to the theme of risk perception, dissemination and partnership programs are carried out through direct and mediated communication channels at the national and regional levels. The program is in the form of socialization of the NPP program to the community in the potential prospective site location and to the general public through media coverage, seminars, exhibitions, workshops, and education programs. Meanwhile, the measurement of public acceptance of nuclear power plants is also carried out through polling. Each activity is carried out by applying the principle of transparency so that the public gets balanced information related to NPPs.

The Indonesian government is ready to operate NPPs to satisfy the country's energy demands. Government agencies that act as promoters and regulators, project owners, technology vendors, construction contractors, and human resources are ready to perform their respective tasks to meet the NZE targets.

5. Conclusion

This study provides an overview of the main NEP-related themes researched in the last two decades. Several types of analyses were discussed, such as co-authorship, citation, and co-occurrence, based on the formulated problem, that is, the development of publication trends based on year, country, author, and the most productive source, as well as the most influential keywords on energy policy and nuclear energy. The number of NEP-related publications has grown significantly since the Fukushima accident, indicating this theme is gaining interest. The US is the leader in NEP research, contributing the largest number of publications from research institutions. The leading author with the highest number of publications and citations is W. Poortinga from Cardiff University, UK. Energy Policy is the most prominent journal for NEP research. This study identified five emerging themes in NEP since 2002 and critically analyzed each theme to identify research gaps that provide an overview for future research directions. First, future nuclear fuel research should focus on extending the fuel cycle, reducing radiotoxicity, improving the stability of spent fuel, and utilizing thorium-uranium nuclear fuel. Second, future research on the Fukushima accident should investigate safety improvements such as incorporating health risks from a radiation protection perspective, strengthening the monitoring of radioactivity in food, and maintaining safety standards through environmental remediation. Third, the risk perception of nuclear energy continues after the Fukushima nuclear accident, particularly in Southeast Asian countries that are expected to use nuclear energy in the future. Fourth, in an effort to address energy and climate issues, energy transition should first examine how technologies for low-carbon energy transition could impact social justice issues. Finally, the contribution of renewable energy to the provision of sustainable energy. A case study of NEP implementation in Indonesia, which is ready to build and operate NPPs with technical and regulatory support, was discussed.

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