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Global research on nuclear energy in the context of health and environmental risks, considering economic interests

Doris Klingelhöfer | **Markus Braun** | **Gerhard M. Oremek** | **Dörthe Brüggmann** | **David A. Groneberg**

Goethe University, Institute of Occupational, Social and Environmental Medicine, Frankfurt, Germany

Correspondence
Doris Klingelhöfer, Goethe University, Institute of Occupational, Social and Environmental Medicine, Theodor-Stern-Kai 7, 60590 Frankfurt, Germany.
Email: klingelhoefer@med.uni-frankfurt.de

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Abstract

The question of whether nuclear energy—as a source with relatively low carbon dioxide emissions—can be classified as a sustainable energy source has come into focus in connection with climate change. There is a controversy over securing independence from fossil fuels and gas supplies from other countries through a revival of nuclear energy. On the other hand, some viewpoints are critical: the handling of nuclear waste and the still unclear risks to human health and the environment, especially in light of recent perils from Russian military attacks on Ukrainian nuclear plants. To evaluate the worldwide publications on nuclear energy under health and environmental aspects, socio-economic parameters were included to provide an informed background for all stakeholders, from scientists to decision-makers. The correlation between the number of nuclear power plants and the publication output of the countries is proven to be highly significant. Thus, the operating countries publish the most. It has been shown that the development and economic use of nuclear energy are major stimuli for scientific endeavors. Reactor accidents have also spurred research. Mathematical risk modeling has been the area with the highest citation rate to date, but environmental and health aspects have become more important, especially after major accidents. The results show the importance of economic interests in research on nuclear energy from health and environmental aspects. Against the background of transnational hazards, global research participation should be encouraged. Moreover, the international debate should not ignore the reality of threats and their possible impacts.

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KEYWORDS

atomic power, chernobyl, Fukushima, nuclear power plant, research incentives

1 | INTRODUCTION

It is a self-evident and compelling prerequisite for present and future energy production and consumption that fossil fuels are no longer tolerable, not only because their availability is limited. They also emit enormous amounts of carbon dioxide into the atmosphere, fueling the greenhouse effect. Thus, the debate about the importance of nuclear energy under the flag of sustainability is rekindled due to its enormous capacity and low carbon emissions (Marques, 2014) and the often still considered insufficient supply of renewable energy sources such as wind and solar (Brook et al., 2014).

As a result, after decades of slow growth and even a decline in the number of nuclear power plants in many countries, there is currently frequent talk of a revival (Ramana, 2009). Nuclear energy has again become a focus of renewed scientific and public interest as the effects of climate change threaten global security, ecological diversity, and human welfare due to rising carbon dioxide emissions in the light of climate change. On the other hand, the risks of nuclear meltdowns, their impact on human health and the environment, and the unresolved issue of nuclear waste are fueling a controversial debate (Ramana, 2018). In particular, three incidents demonstrate how vulnerable nuclear power plants are to unforeseen events such as natural disasters or armed conflict and the serious consequences they can have: the Fukushima nuclear power plant accident in 2011, caused by earthquakes and tsunami in Japan (UCSUSA, 2013) and the ultimate MCA (maximum credible accident) in Chernobyl. The recent increase in radiation levels at Chernobyl, which was up to 20 times above normal following heavy fighting between Russian and Ukrainian forces in the region at Russian President Putin's war of aggression also illustrates the risk (Turner, 2022).

In many countries, however, there have also been accidents in plants involving the release of ionizing radiation. This is harmful to the biosphere and humans through the inhalation of dust particles or the consumption of contaminated food, water, or milk. It endangers not only the biosphere of the producing countries but also a more or less large territory in the surrounding area, depending on the weather conditions. Releases of nuclear isotopes are responsible for high health risks mainly due to DNA damage, such as cancer, especially in children and young people. Besides, psychological diseases and direct effects of the accidents such as fires and explosions can also cause damage (NCI, 2022). The major historical accidents have claimed several thousand lives, exposed millions of people to radiation, and caused diseases. Vast areas were contaminated for a long time into the distant future, affecting the earth and water spheres as well as fauna and flora (Christodouleas et al., 2011).

The current upswing in nuclear power plants being nevertheless experienced stems from the fact that nuclear energy is to be given the "green energy" label and used again increasingly as an interim solution until renewable energy sources are ready to meet the world's energy needs. In addition, the rising prices of fossil fuels are causing a resurgence of interest even in countries that scaled back nuclear energy years ago. Nevertheless, the economic viability of nuclear power is widely seen as an obstacle due to high costs and financial uncertainties (Ramana, 2009).

The controversial positions on the classification of nuclear energy, advocating either a revival or a steady dismantling of nuclear power plants, have a major impact on future energy strategies on political, economic, technical, and scientific principles. That also leads to massive implications for environmental safety and human health. In addition, it is necessary to review and discuss the opinion that renewable energy supply is also currently more potent than often assumed. So, at the very least, it should be questioned whether nuclear energy can be considered sustainable in the context of environmental risks and human health, which certainly play a role in defining the term "sustainability" or "green," especially because many consequences are still unknown (Christodouleas et al., 2011). In this context, the handling and storage of nuclear waste, with its remaining uncertainties for future generations, and still inadequate reactor safety are also challenges that still need to be addressed (Karakosta et al., 2013; Pearce, 2012).

These days, in March 2022, news spread of a fire at Europe's largest nuclear power plant in Zaporizhzhya, caused by a Russian attack on Ukraine. Fortunately, the fire broke out not in the reactor but in an adjacent building (Ives et al., 2022). Although the safety of modern plants can withstand an airplane crash, a targeted terrorist attack on the reactor can cause devastating damage (Tian & Lee, 2021). This incident illustrates the danger that can befall the environment and people, as no one can foresee what the future will bring, which is largely what "sustainability" should mean.

Therefore, the present study aims to provide a scientific basis for professional discussion on the worldwide publication efforts in the field of *Nuclear Energy under Health and Environmental aspects* (NEHE) by applying advanced bibliometric methods suitable for evaluating and assessing the publication output from different relating aspects. The results and their interpretation provide insights into the research background, its distribution, trends, and incentives, and requirements for all stakeholders, ranging from decision-makers to funders to individual scientists planning for the future.

2 | MATERIALS AND METHODS

Content-based publications were collected by searching Clarivate's *Web of Science* (WoS) Core Collection, one of the most comprehensive online databases for scientific literature. Providing additional citation numbers for each article, it serves as a standard database for the analyses embedded in the methodological platform *New Quality and Quantity Indices in Science* (NewQIS; Groneberg-Kloft et al., 2009), on which the present study is based.

The search term used is an elaborated string consisting of various synonyms and combinations, ensuring the highest reliability for the representativeness of the data included in the analysis. The aim here was to achieve the highest number of entries and at the same time reduce the number of false, i.e., off-topic entries.

Search string: (TOPIC) “nuclear power” OR “atomic power” OR “nuclear energy” OR “atomic energy” OR “nuclear reactor*” OR “nuclear accident*” OR “Nuclear plant*” OR “reactor accident*” OR “radiological accident*” OR “nuclear waste” OR “atomic waste” OR “radiological waste” OR Chernobyl OR Fukushima OR Harrisburg OR Windscale OR Kyshtym.

After applying the search term in title, abstract, and keywords as topic search, entries were filtered by the relevant research areas that were the focus of the analysis by including only areas related to human health and ecological issues.

The metadata determined for the publications related to NEHE found were stored in an Microsoft Access database and sorted according to analysis parameters. Subsequently, manual corrections had to be made for participating institutions, authors, and subject areas to standardize the data due to incoherent entries.

Data were analyzed by their temporal and geographical characteristics, using established bibliometric parameters such as the number of publications and citations per year, and advanced parameters related to nuclear power research such as the number of nuclear power plants and accidents per country (The Guardian, 2022). The scale for the assessment of events involving the release of radioactive material into the environment or human exposure was developed by the *International Atomic Energy Agency* (IAEA, 1994). The inclusion of research content characteristics allows the assessment of incentives and requirements of the global research effort. Countries of origin were determined by address or affiliation, with one multinational item counting for each partner country.

In addition, a keyword analysis was performed to identify research priorities and their attention in the scientific community. Socioeconomic values were also included to take into account national characteristics and to evaluate the countries' contributions accordingly. Here, population figures and economic strength as gross domestic product (GDP) per publishing country were included. A Data set from 2017 was used as it provides the most comprehensive data (UIS. Stat, 2022). For all parameters based on ratios, an analytic threshold of at least 30 articles on NEHE was applied to reduce bias from countries with very few publications.

Data on nuclear power plants were retrieved from the IAEA (1994).

For visualization, van Eck and Waltman's VOSviewer (van Eck & Waltman, 2010) was used to display clusters of keywords (threshold 130 coincidences) and their citations. Density equalizing map projections (DEMPs) are combined by default with NewQIS results to display geographic publication patterns. DEMPs are based on physical algorithms developed by Gastner and Newman (Gastner & Newman, 2004). They were created using the ArcGIS geographic information system.

2.1 | Methodological limitations

The applied methodology has some limitations that need to be considered. First, the searched online database WoS and the applied search strategy cannot cover all publications on NEHE aspects, because not all journals are listed in the Core Collection indices. The premise of the best possible representativeness of the data limits the amount of data by applying an appropriate search string. Therefore, some items may not be covered by the search strategy. In addition, as has often been reported, WoS has a bias toward English-language literature, so few publications are listed in other languages (Chavarro et al., 2018).

Second, because of the intensive manual correction work that the final database had to undergo, the results are not perfectly repeatable, as each researcher has his or her own procedures.

Third, citation analyses can only indicate the quality of publications in a country. It is better to speak of the recognition of publications in the scientific community.

Fourth, the development of country contributions and the sum of publications must be seen in the historical context of the independence of former confederations of states such as the USSR. In particular, the absolute numbers of publication output must be interpreted in this context.

3 | RESULTS

In total, 26,373 publications (n) could be found by the application of the search strategy in WoS. Of these, $n = 17{,}674$ publications (67.02%) were published as original articles, $n = 2969$ as proceedings papers (11.26%), $n = 1762$ as editorial material, and $n = 1066$ as reviews. English was by far the most frequently used publication language (95.53%). Russian followed at a great distance with only 1.55%, French with only 1.07%, and German with 0.86%. All other document types and publication languages were represented only marginally.

3.1 | Research foci

The analysis of the occurrence of keywords revealed three main thematic clusters of NEHE research. First, a publication cluster dealing with ionizing radiation and its effects on human health was identified, mainly concerning the Chernobyl power plant accident in 1986 as the most frequently used keyword in the whole analysis (blue cluster in Figure 1a).

Second, it was dealt with the contamination, accumulation, and transfer of radioactive elements in soil, sediment, and water, as well as the effects on fauna and flora (red cluster in Figure 1a). Third, a cluster on the management of nuclear disasters and the importance of nuclear energy as a low-carbon emitter in terms of measures to reduce carbon dioxide levels in the atmosphere in the context of climate change (green cluster in Figure 1a).

Looking at the number of citations received for each keyword shows the high recognition of green cluster publications. The topics of risk perception and trust in nuclear energy stand out here. This was followed by articles on climate change and articles comparing the risks of nuclear power with those of atomic bomb survivors. Research related to the transport of radioactive material in sediments and soils was also still widely cited. In addition, publications on the risk to children, cancer as an impact of the blue cluster, and the classification as renewable energy, in turn, of the green cluster were still relatively frequently cited (Figure 1b).

The most frequently cited publications are mainly related to modeling environmental risks, risks to human health such as thyroid cancer, and risk assessment (Table 1). The publishing journals of the top 10 cited articles are mostly not among the high-ranking journals that typically publish the most cited articles on a given topic (Groneberg et al., 2019).

The subject area *Mathematics*, represented by the journal *Risk Analysis*, is the leading one in this analysis. *Energy and Fuels*, the second-ranked area, is represented by *Renewable and Sustainable Energy Reviews*. The category *Meteorology & Atmospheric Sciences* is listed for the journals *Australian Meteorological Magazine* and *Atmospheric Chemistry and Physics*. *Environmental Science* is only ranked 11th. As it refers to articles that are more recent, it will likely move up in the ranking in the future. It represents the categories *Sustainability Science* and *Ecological Economics*.

Looking at the development of the most frequently assigned WoS topic categories (Figure 2), it is noticeable that the share of environment-related topics has increased, while the share of engineering and material sciences has decreased over time since the mid-1980s. Medical topics also began to increase at that time but declined again in the mid-2010s.

3.2 | Evolution of publication patterns

The first article on NEHE included in the analysis database dates from 1920. Until after World War II in 1946, topic-related articles were published only sporadically. Subsequently, a steady annual publication output was noted at the double-digit level. From 1977 on, three-digit annual figures were published with an increasing tendency until 1996 as an early maximum ($n = 715$). Small publication peaks during this period were in 1979 ($n = 208$), 1987 ($n = 331$), and 1991 ($n = 515$).

After 1996, publication numbers briefly declined, only to increase again starting in 2004, followed by a period characterized by a very steep increase reaching a peak of $n = 1291$ articles on NEHE in 2020. The trend in citation numbers

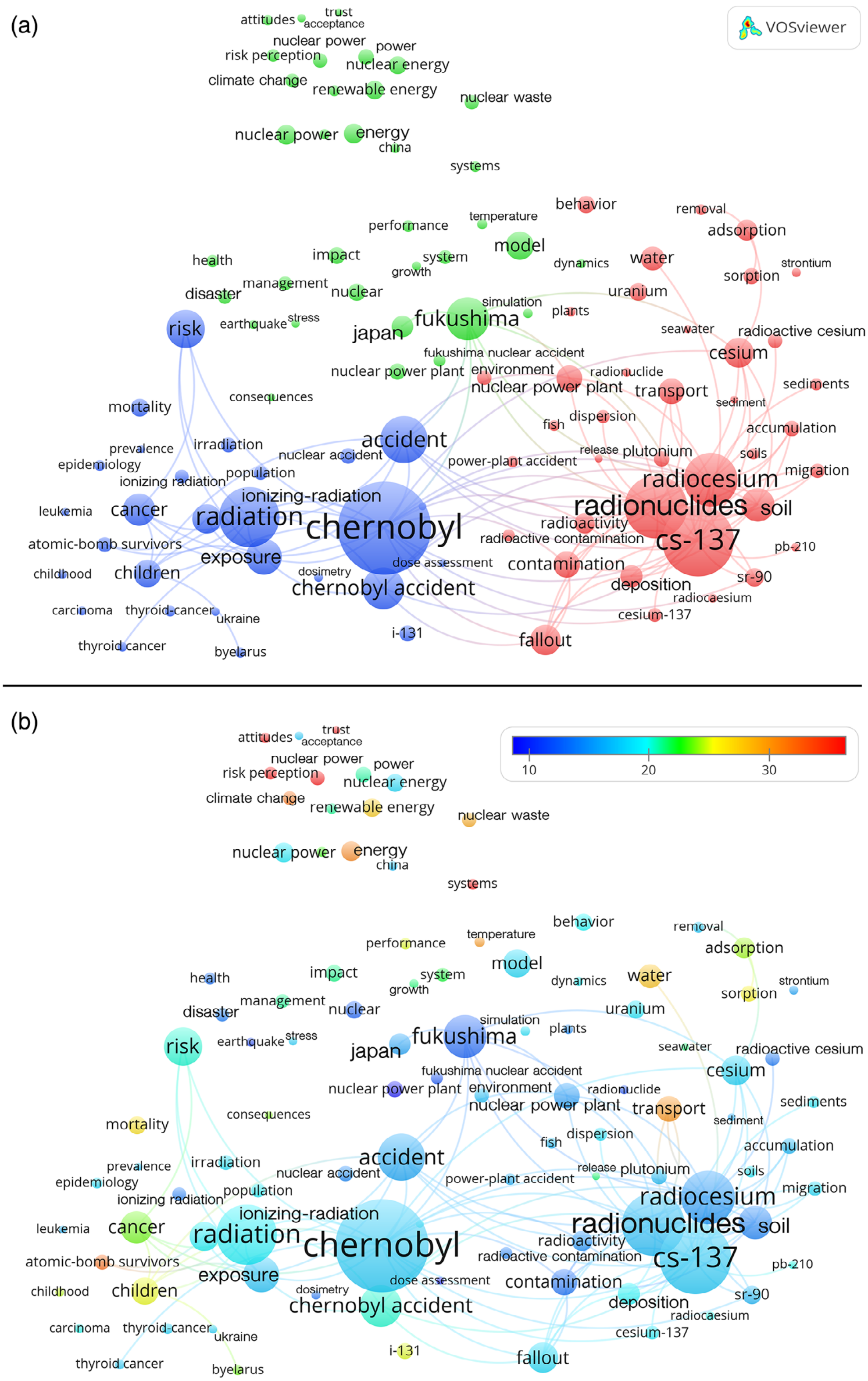

FIGURE 1 Keyword analysis of NEHE research (threshold 130 co-occurrences). (a) Thematic clusters. *Blue*: nuclear accident exposure, risk to human health from ionizing radiation, mainly Chernobyl. *Red*: environmental contamination by radioactive elements; risks to biosphere; adsorption in soil and sediment. *Green*: management of nuclear disaster, mainly Fukushima; risk perception and nuclear energy as sustainable energy in light of climate change (mainly separate foci with no connection to each other). (b) Citation numbers of keywords applied.

TABLE 1 Ten most cited publications on NEHE, c = number of citations IF = Impact factor from Web of Science 2021 from the year in which the article was published).

Authors	Country	Year	c	Title	Journal	IF
R. R. Draxier, G. D. Hess	USA, Australia	1998	2168	An overview of the HYSPLIT_4 modeling system for trajectories, dispersion, and deposition	Australian Meteorological Magazine	0.583
M. L. Finucane et al.	USA, Saudi Arabia	2000	1475	The affect heuristic in judgments of risks and benefits	Journal of Behavioral Decision Making	1.639
E. T. Kimura et al.	USA	2003	1172	High prevalence of BRAF mutations in thyroid cancer: Genetic evidence for constitutive activation of the RET/PTC-RAS-BRAF signaling pathway in papillary thyroid carcinoma	Cancer Research	8.649
R. Saidur, K. Y. Leong, H. A. Mohammed	Malaysia	2011	1169	A review on applications and challenges of nanofluids	Renewable and Sustainable Energy Reviews	6.016
A. Stohl et al.	Norway, Austria	2005	1151	Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2	Atmospheric Chemistry and Physics	3.495
D. J. Lang et al.	Germany, USA, Switzerland, Netherlands, South Africa, UK	2012	1111	Transdisciplinary research in sustainability science: Practice, principles, and challenges	Sustainability Science	2.189
D. J. Brenner et al.	USA, UK, Japan	2003	1087	Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know	PNAS	10.272
P. Slovic	USA	1999	968	Trust, emotion, sex, politics, and science: Surveying the risk-assessment battlefield	Risk Analysis	1.366
R. York, E.A. Rosa, T. Dietz	USA	2003	954	STIRPAT, IPAT, and ImPACT: analytic tools for unpacking the driving forces of environmental impacts	Ecological Economics	1.230
P. Slovic	USA	1993	922	Perceived risk, trust, and democracy	Risk Analysis	1.366

was similar to that of publications, with steady ups and downs until the short interval of the collapse in publication numbers at the turn of the millennium, when citation numbers had small plateaus (1998/1999, c = 12,293/12,275 and 2003/2004, c = 11,581/11,615). The highest annual citation count was reached in 2012 (c = 20,449), followed by a subsequent steep decline (Figure 3a).

To interpret the evolution of publication patterns on NEHE, it is important to compare them with those of biomedical research as a whole, as listed in the *Science Citation Index Expanded* (SCIE) of the WoS. From the end of World War II, the indexed SCIE publications show a nearly linear increase with minor deviations. The trend in publications follows that of SCIE publications with a few exceptions, shown in Figure 3b by positive slopes beginning in 1945, 1956, and 1986, but quickly converging back to the trend in SCIE publications. However, the increased publication period from 1986 onward continued until the decline in NEHE articles in 1996.

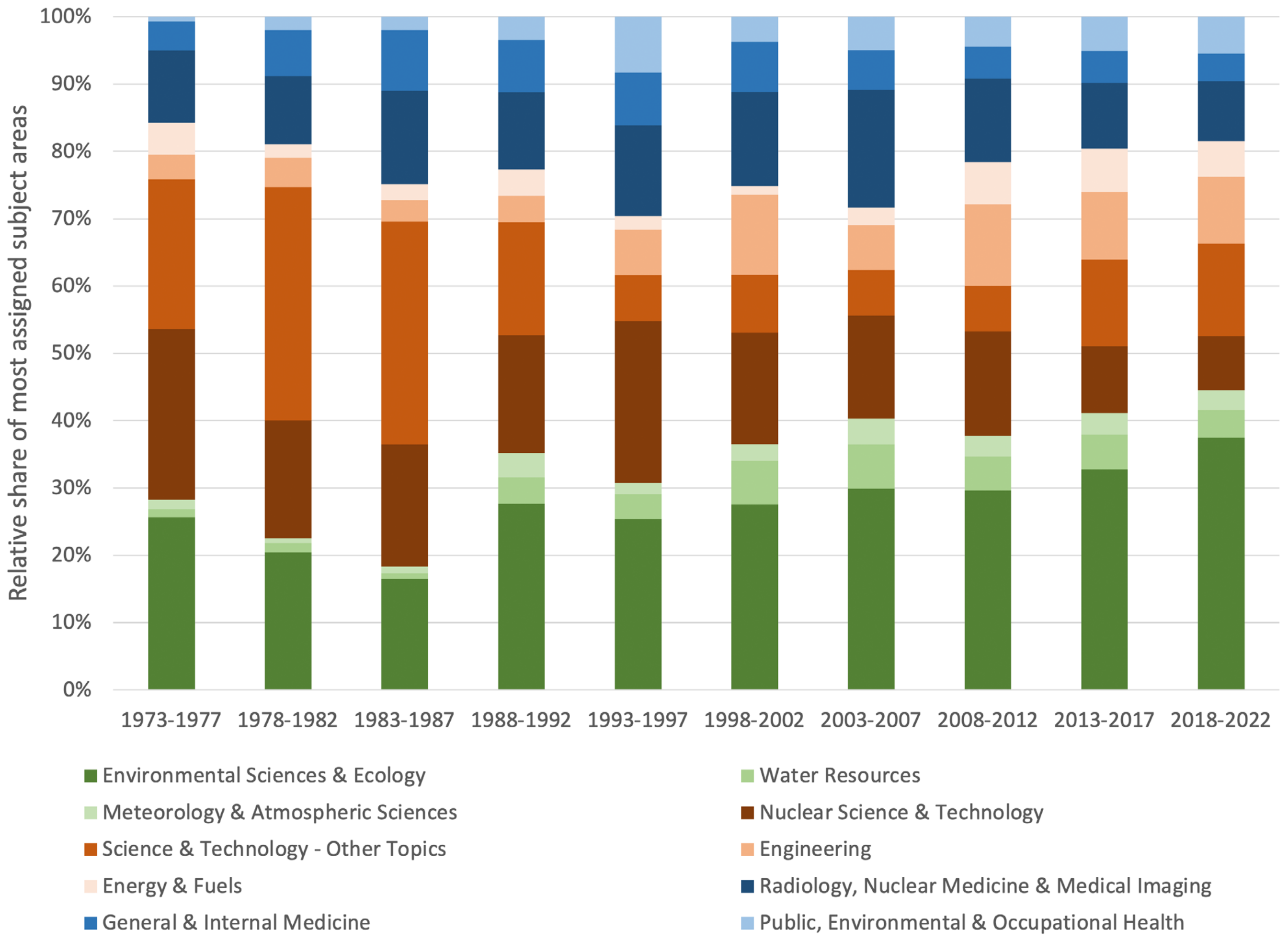

FIGURE 2 Evolution of the share of most assigned WoS categories in 5-year intervals from 1973 to 2022. Color shading: green = environmental issues, brown = technical and material issues, and blue = medical issues.

3.3 | Geographical publication patterns

Of the total database ($n = 26{,}373$), $n = 23{,}130$ publications could be assigned to at least one country of origin (87.70%). One hundred forty-nine countries participated in NEHE research, with the United States being the country with the most publications ($n = 5362$). The top 5 also included Japan ($n = 3798$), the United Kingdom ($n = 2151$), France ($n = 1667$), and Germany ($n = 1548$). Russia ranks 6th with $n = 1495$, followed closely by China ($n = 1458$) and Ukraine ($n = 1151$). Belarus also ranks in the top 20 with $n = 473$ articles on NEHE (Figure 4a).

The citation numbers resulted in a similar distortion of the world map, except for the lower numbers of Russia, China, and Ukraine (Figure 4b).

For citation rates (cr) calculated as the number of citations per article from countries with at least 30 articles on NEHE (threshold), a different order of the top 5 countries emerges: Monaco ($n = 51$, $c = 1998$, $cr = 38.42$), Saudi Arabia ($n = 87$, $c = 2929$, $cr = 33.67$), Australia ($n = 422$, $c = 14{,}012$, $cr = 33.20$), Malaysia ($n = 109$, $c = 3140$, $cr = 28.80$), and the Netherlands ($n = 365$, $c = 10{,}360$, $cr = 28.38$; Figure 4c).

The impact of power plant accidents such as the Chernobyl ultimate MCA and the Fukushima Daiichi disaster can be seen in the increase in the regional publication numbers of the former USSR countries and Japan in the evaluation intervals following these accidents (Figure 5).

The 10 institutions with the most publications on NEHE were the U.S. DOE (U.S. Department of Energy) with 814 articles, followed by Fukushima Medical University ($n = 601$), University of Tokyo ($n = 468$), Japan Atomic Energy Agency (JAEA, $n = 386$), Russian Academy of Sciences (RAS, $n = 366$), the Institut de Radioprotection et de Sûreté

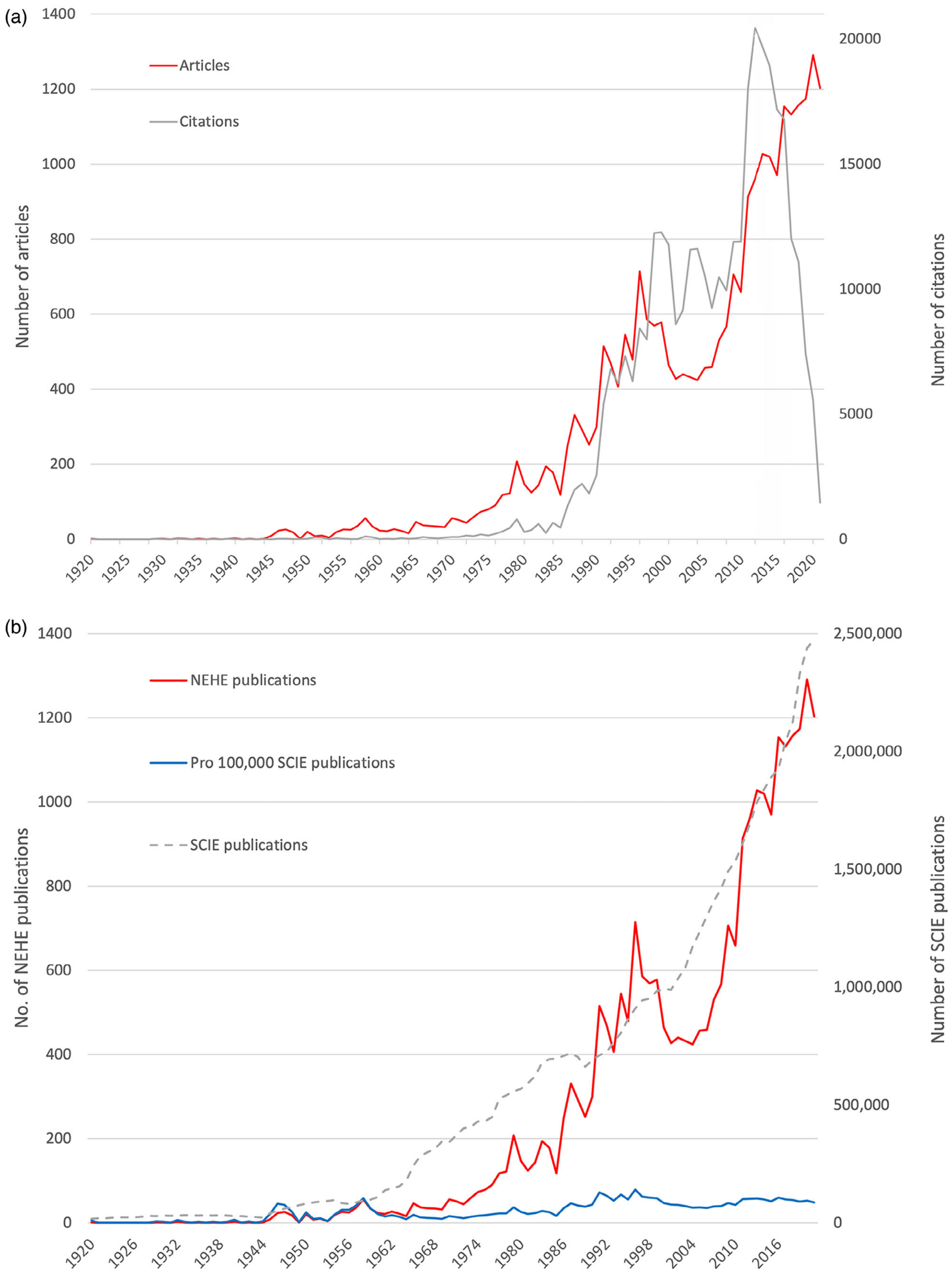

FIGURE 3 Time evolution of NEHE (Nuclear Energy under Health and Environmental aspects) publications, (a) Publication and citation numbers over time. (b) Publication counts, number of all SCIE publications, and number of NEHE publications per 100,000 SCIE publications, SCIE, Science Citation Index Expanded of Web of Science.

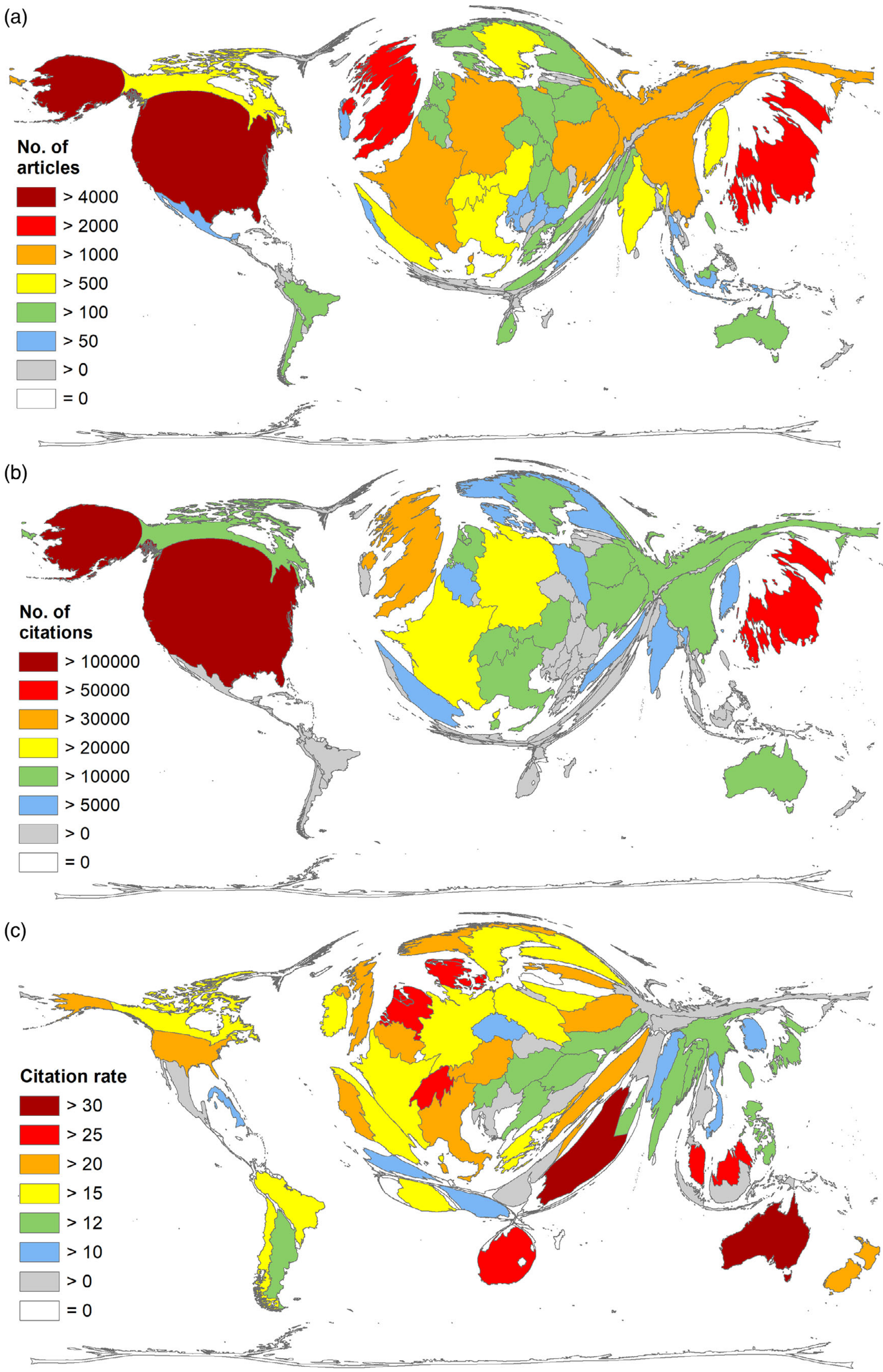

FIGURE 4 Geographical distribution of NEHE articles. (a) Number of articles per country. (b) Number of citations. (c) Citation rate (threshold ≥30 articles on NEHE).

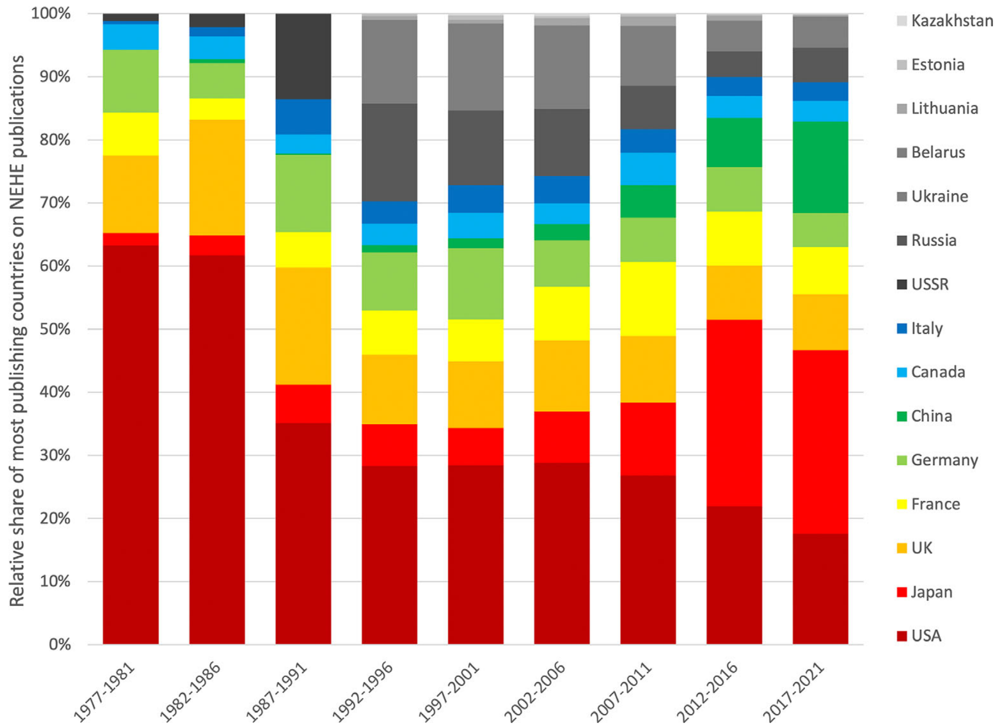

FIGURE 5 Relative share of publications of the countries with the most publications (including USSR and former USSR countries in grayscale) in 5-year intervals from 1977 to 2021.

Nucléaire (IRSN, $n = 360$), International Atomic Energy Agency (IAEA, $n = 340$), Ukrainian Academy of Medical Sciences (UAMS, $n = 250$), and Nagasaki University ($n = 249$). The 10th place was shared by the Chinese Academy of Sciences (CAS) and Kyoto University with 234 articles each.

3.4 | Inclusion of countries' socioeconomic characteristics

Table 2 shows the ranking, considering the number of researchers and gross expenditures on R&D (GERD) in NEHE research per country. This shows the role of some former USSR countries and Eastern European countries. In terms of the number of researchers, Austria, Norway, Finland, and Switzerland are also worth mentioning.

3.5 | Inclusion of country data on nuclear power plants

For the interpretation of the significance of the country figures of nuclear power plants, the number of active plants, the number of decommissioned plants, and the number of accidents in the plants per country were included (IAEA, 2021).

The linear regression and the correlation (Spearman) were in all three evaluations significant ($p < 0.0001$; Figure 6a). The calculation of the residuals of the linear regression between the number of articles and the number of active plants is shown in Figure 6b and indicates the countries with disproportionately high or low publication output.

3.6 | International partnerships

The international network is wide-ranging, but has its main axes signifying the USA, the UK, Japan, Ukraine, France, and Russia. The USA is the main nod within the network. The main bilateral partners are USA/Japan, $n = 334$

TABLE 2 Ranking of top 20 (threshold 30 publications) in terms of RGERD = ratio of the number of articles to Gross Expenditures in Research and Development in ppp$ (purchasing power parities in Dollars) and RRES = ratio of the number of articles to the number of researchers in FTE (full-time equivalents; UIS.Stat, 2022).

Country	GERD in bn ppp$	R_{GERD}	Country	Researcher in 10,000 FTE	R_{RES}
Ukraine	2.26	504.55	Ukraine	4.22	270.61
Belarus	1.01	466.38	Lithuania	0.87	152.16
Lithuania	0.86	155.10	Austria	4.75	143.09
Croatia	0.95	98.28	Norway	3.36	128.45
Serbia	1.01	93.68	Croatia	0.78	119.00
Slovakia	1.49	91.30	Finland	3.70	118.23
Bulgaria	1.12	88.14	Switzerland	4.61	109.14
Estonia	0.57	85.92	Estonia	0.47	104.84
Greece	3.54	72.91	Slovakia	1.32	103.32
Norway	6.97	61.96	Sweden	7.31	93.26
Finland	7.15	61.27	Slovenia	0.93	80.64
Kazakhstan	0.57	59.85	Romania	1.75	78.21
Slovenia	1.41	53.06	UK	28.97	74.26
Romania	2.68	51.12	Greece	3.50	73.71
Pakistan	2.25	48.99	Belgium	5.40	73.69
Austria	14.66	46.40	Bulgaria	1.51	65.59
Hungary	3.85	44.16	Serbia	1.46	65.26
UK	51.03	42.15	Hungary	2.84	59.80
Sweden	17.84	38.23	Czech Republic	3.92	57.94
Russia	42.38	35.28	Denmark	4.54	56.57

collaborations; the USA/France, $n = 254$ collaborations; the USA/the UK, $n = 243$ collaborations; and the USA and Ukraine, $n = 225$ collaborations. Other former USSR countries are also participating in international collaboration to a higher extent than in other research fields (Groneberg et al., 2019).

3.7 | Research institutions

Table 3 lists the research institutions that have published most frequently on NEHE.

4 | DISCUSSION

Publication patterns on NEHE mainly follow historical and economic events in the development of nuclear energy and accidents that have occurred at the plants. That is also reflected in the composition of the major players in global research. The first scientific steps toward nuclear energy use were taken in Europe by scientists such as Henri Becquerel, Marie Curie, Ernest Rutherford, Enrico Fermi, and Otto Hahn, to name but a few (World-Nuclear.org, 2020). Thus, the first publications in our database appeared in Nature as of 1920 on different possibilities of nuclear energy use (Lodge, 1920). Beginning in 1945, after World War II, publication numbers on NEHE started to increase slightly, including a focus on the freedom for scientists to conduct studies away from use as weapons or national interests (Anonymous, 1945a; Anonymous, 1945b). In the USA in 1946, the Atomic Energy Commission (AEC) was established to control nuclear energy for peaceful utilization (USDE, 2022). In the same year, the *Institute of Physics and Power Engineering* (FEI) was launched in the USSR to develop nuclear power technology (World-Nuclear.org, 2020). Electric power was first generated in 1951 in an experimental Breeder reactor in Idaho (USA) that made four

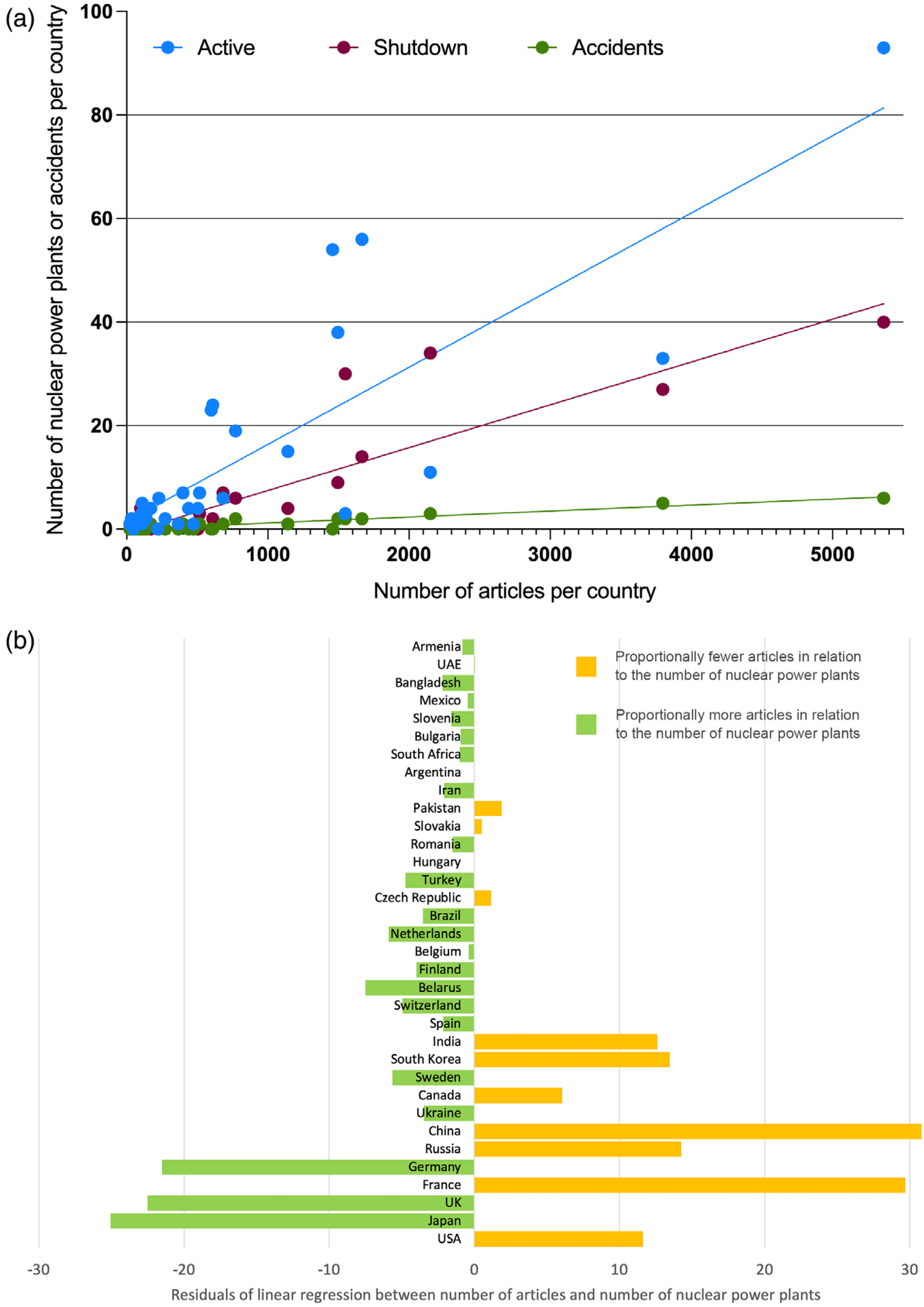

FIGURE 6 Association of the number of articles on NEHE and country data on nuclear power plants. (a) Linear Regression of the number of articles and the number of active plants ($r = 0.78$), the number of shutdowns ($r = 0.64$), and the number of accidents ($r = 0.67$) in producing countries. (b) Residuals of the linear regression between the number of articles and the number of active plants.

light bulbs light up (de Kern, 2022; USDE, 2022). In 1953, U.S. President Eisenhower initiated the "Atoms for Peace" program with a main scientific effort for civil nuclear energy in the USA. In 1955, the first city there was also supplied with Energy from a nuclear power plant (USDE, 2022). Also in 1955, the first *UN International Conference on the Peaceful Uses of Atomic Energy* was held in Switzerland. The IAEA was founded in Austria in 1957 to promote the peaceful uses of nuclear energy. Two severe incidents in nuclear reactors occurred already in 1957: Windscale, UK, where a unit caught fire and melted, resulting in an enormous emission of radioactivity. This was a five-scaled accident

TABLE 3 Most-publishing research institutions on NEHE.

Institution	Country	Articles	Citations	Citation rate	Full name
US DOE	USA	814	15,966	19.61	U.S. Department of Energy
Fukushima Med Univ	Japan	601	6262	10.42	Fukushima Medical University
Univ Tokyo	Japan	468	7436	15.89	University Tokyo
JAEA	Japan	386	6696	17.35	Japan Atomic Energy Agency
RAS	Russia	366	3074	8.40	Russian Academy of Science
IRSN	France	360	5503	15.29	Institute de Radioprotection et de Sûreté Nucléaire
IAEA	Austria	340	7078	20.82	International Atomic Energy Agency
UAMS	Ukraine	250	4918	19.67	Ukraine Academy of Medical Science
Nagasaki Univ	Japan	249	4497	18.06	Nagasaki University
CAS	China	234	4108	17.56	Chinese Academy of Science
Kyoto Univ	Japan	234	3581	15.30	Kyoto University
NASU	Ukraine	214	1499	7.00	National Academy of Science of Ukraine
BARC	India	209	2744	13.13	Bhabha Atomic Research Centre
Univ Tsukuba	Japan	207	4998	24.14	University Tsukuba
NIH	USA	206	6477	31.44	National Institutes of Health
CEA	France	205	3310	16.15	Commissariat à l'énergie atomique et aux Energies Alternatives

according to INES. Another accident happened in Kyshtym, Russia. The INES 6 accident was caused by the explosion of a tank containing high-level waste resulting in a significant release of radioactive material (UCSUSA, 2013). The following year, 1958, was the first year that annual publication numbers showed a first peak. The number of citations reached triple digits mainly due to references to articles about the Windscale accident, while the Kyshtym accident was not mentioned for the first time until 1979 and was covered primarily by Russian scientists.

In the 1960s, the commercialization of nuclear energy began with plants in the USA, Canada, France, the UK, Germany, and the Soviet Union (USSR), initiating a steady increase in annual publication numbers. In Kazakhstan (former USSR), the new fast neutron reactor was put into operation in 1972 (de Kern, 2022; World-Nuclear.org, 2020). In 1974, the AEC's responsibilities were divided into two newly established agencies: the *Energy Research and Development Administration* (ERDA) for R&D and the *Nuclear Regulatory Commission* (NRC) for regulatory actions. Then, in March 1979, the worst U.S. accident occurred near Harrisburg (Three Mile Island), caused by "mechanical malfunction and human error" (USDE, 2022) leading to a partial meltdown. It is rated 5 on INES (IAEA, 1994). The Department of Energy (DOE), established in 1977, initiated the Three Mile Island R&D program in 1980 to develop safer technologies. The results of this study show that, by analogy, the number of publications increased in triple digits starting in 1977 and reached a first peak in 1979, the year of the Harrisburg accident.

From 1980 onward, the nuclear power industry experienced a period of stagnation, as only few new reactors were built, and the share remained almost constant at 16%–17%. Nevertheless, publication numbers in the late 1980s reached higher annual figures compared to the overall SCIE-publication trend due to the accident at the Chernobyl nuclear power plant (Ukraine) in 1986, which is considered the world's worst nuclear power plant disaster to date. An explosion resulting from a power surge destroyed an entire unit and caused exceedingly high radiation exposure throughout Russia and Europe. It is rated 7 on INES (IAEA, 1994). This period of increased deep interest in NEHE research after Chernobyl is reflected in the plateau of NEHE articles per SCIE article, which, however, began to decline again in 1996. However, this period of waning interest was marked by two plateaus with a high number of citations, indicating the high level of interest in studies on the effects of Chernobyl, since it was primarily research on Chernobyl that provided the knowledge on cancer due to radiation exposure (NCI, 2022). During this time, the proportion of medical and environmental focus areas in NEHE research has increased accordingly.

With the commissioning of the third generation of reactors in Japan in the late 1990s, the nuclear power industry began to recover, as did the publication numbers. This was also due to global demand, especially in rapidly developing countries, and stable availability. In addition, concerns about carbon dioxide emissions came to the fore as the impact of climate change was recognized.

The terrorist attack in 2001 by targeted aircraft crashing into the World Trade Center in New York, the attack in history that claimed the most lives, raised questions about the impact of an attack on nuclear sites. As a result, research interest continued to increase during this period (Cravens, 2002), as evidenced by the end of the decline in annual publication numbers.

Then, in 2011, the accident occurred at the Fukushima Daiichi nuclear power plant. It was caused by an earthquake and tsunami in Japan. The accident was consistent with INES 5 (IAEA, 1994) and demonstrated the vulnerability of nuclear power plants to natural disasters, providing an additional cause for increased scientific engagement. This led to an increase in environmental research priorities while the proportion of medical foci began to decline. This can certainly be explained by the fact that the immediate effects of the Fukushima accident on human health were not as noticeable as those of the Chernobyl accident.

It is said that "German Angst" is the driving force behind the phase-out of the majority of nuclear power plants after the Fukushima accident and the decision of the total phase-out for 2023. However, other countries have also opted for "nuclear-free" energy status (e.g., Italy, Belgium, Switzerland), while others have decided that they will remain "nuclear-free" (e.g., Denmark, Portugal, Austria). Nevertheless, many countries maintain their nuclear plans, for example, the USA, the UK, France, and Russia, or even plan to build new nuclear power plants (Appunn, 2021). The question of the importance of nuclear energy as renewable energy to replace fossil fuels in the face of climate change also led to an increase in the number of publications in 2012 (Karakosta et al., 2013). These facts certainly have contributed to the publication peak of 2013.

The significant decline in citation numbers after 2013 is not related to a waning interest in NEHE research but the effect of the methodological phenomenon known as the citation half-life, which is estimated to be about 8 years for biomedical research. It defines the time it takes publications to reach half of their maximum citation count (Della Sala & Crawford, 2007). Therefore, it can be assumed that the citation figures for the last few years will also show an upward trend in a later evaluation.

The last few years have been characterized by a persistent and sharp increase in the number of publications with the increasing importance of environmental research. Currently, China and India in particular are planning a massive expansion of nuclear energy, so its future importance must be linked to East Asian development (World-Nuclear.org, 2020). Therefore, China's contribution to publication output on NEHE also increases in the last interval of the evaluation period. This is consistent with Chinese efforts to increase national scientific output in principle (citation), although the ranking of current research lags behind other research areas and indicates a rather cautious attitude toward NEHE research. The reason for this is certainly the planning of 15 nuclear power plants at present. This makes China the country with the most committed construction intentions.

Otherwise, national publication numbers are mostly in line with national economic interests. The significant correlation between the number of articles on NEHE and the number of active nuclear power plants points to this relationship. This explains the leading position of nuclear energy-producing countries, especially those that were the first to start using power plants economically. However, the increasing research interest after nuclear accidents or incidents is also remarkable and can be seen in the increasing trends of publication numbers afterward and the comparison of the residuals of the linear regression between publication numbers and the number of active plants.

The unusually high contribution of the former USSR countries compared to other research areas (Groneberg et al., 2019) is therefore also explainable and unique to NEHE research. This also leads to its high ranking in terms of socio-economic analyses. The efforts of these countries increased after the Chernobyl accident if we look at the assessment intervals from 1987 onward. However, the assessment shows a decreasing trend from the beginning of the 2000s.

International cooperation, especially the comparatively high participation of former USSR countries, also has its incentives in the regional investigation of accident sites such as Ukraine and Belarus.

The high level of awareness of mathematical risk modeling resulted in a high ranking of the WoS category "Mathematics" as measured by the citation rates and the rank of the corresponding articles among the most cited articles. The assessment of the countries with the highest citation rates should also be seen in the context of the most frequently cited articles in which they participated. Monaco, the country with the highest citation rate for this study, is the location of the IAEA environmental laboratories. That includes the departments of terrestrial and marine environmental studies as well as the radiometric and radioecological laboratory. Its goal is to evaluate measures to mitigate the effects of radionuclides on climate change, biodiversity, and habitat degradation, among others (IAEA, 2022). The IAEA, with its headquarters in Austria, is one of the top 10 publishing institutions, along with national government agencies and research institutions. First and foremost is the U.S. Department of Energy (DOE), which is involved primarily through its subordinate National Laboratory System with its 17 regional research facilities. Otherwise, the Japanese Atomic Energy Agency and some universities are represented in the ranking of the most important institutions. The science academies of Russia, Ukraine, and China have been frequent contributors, as have France's government research institutions. Thus, the institutional landscape is shaped just like the national one, with the exception that UK and German institutions are not among the top-performing institutions in NEHE research.

The declaration of nuclear energy as sustainable is clearly in the interest of the nuclear energy-producing companies as well as an incentive for the respective countries, as shown by their scientific interest. In particular, the current effort to become more independent of energy supplier countries is in the foreground. However, the more intensive use of renewable energy sources and the infrastructure required for this is delayed by a possible upsurge of nuclear energy, the displacement effects of which are detrimental to the future energy landscape.

5 | CONCLUSIONS

The debate on the assessment of the risks of nuclear energy, mainly related to the operation and storage of waste, as opposed to its status as low-carbon energy and its need to be independent of other countries, is revitalizing the scientific landscape. The trend toward the environmental aspects of research is beginning to be felt while medical issues are losing weight. The national incentives for research efforts are clearly linked to the presence of nuclear power plants, with major accidents immensely influencing regional efforts. This explains the role of the former Soviet countries in the scientific landscape. Unforeseen events, like the war in Ukraine, turn the tables again as the safety of nuclear plants is questioned under these conditions. Sustainability must be questioned globally and under multidisciplinary approaches that unite a majority of the nations, as impacts do not stop at borders.

AUTHOR CONTRIBUTIONS

Doris Klingelhöfer: Conceptualization (lead); data curation (lead); formal analysis (lead); investigation (lead); methodology (equal); resources (lead); software (equal); supervision (equal); validation (equal); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Markus Braun:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); validation (equal); writing – review and editing (equal). **Gerhard M. Oremek:** Data curation (supporting); investigation (supporting); resources (supporting); supervision (supporting); validation (supporting); writing – review and editing (equal). **Dörthe Brüggmann:** Conceptualization (supporting); methodology (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – review and editing (equal). **David A. Groneberg:** Conceptualization (supporting); methodology (equal); project administration (lead); supervision (equal); validation (supporting); writing – review and editing (equal).

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ORCID

Doris Klingelhöfer https://orcid.org/0000-0003-0716-9872
Markus Braun https://orcid.org/0000-0003-3393-2851

Gerhard M. Oremek https://orcid.org/0000-0001-9729-7274
Dörthe Brüggmann https://orcid.org/0000-0002-4799-3391
David A. Groneberg https://orcid.org/0000-0001-8551-6556

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