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A lead for transvaluation of global nuclear energy research and funded projects in Japan

Eriko Kiriyama [a,*], Yuya Kajikawa [b,c], Katsuhide Fujita [d], Shuichi Iwata [e]

[a] The University of Tokyo, Todai Policy Alternatives Research Institute, Ito International Research Center, 3F 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[b] Graduate School of Innovation Management, Tokyo Institute of Technology, 3-3-6 Shibaura, Minato-ku, Tokyo 108-0023, Japan
[c] Graduate School of Engineering, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan
[d] Faculty of Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-shi, Tokyo 184-8588, Japan
[e] The Graduate School of Project Design, 3-13-16 Minami Aoyama, Minato-ku, Tokyo 107-8411, Japan

HIGHLIGHTS

- Chernobyl accident had limited influence on basic research in nuclear energy.
- Budget allocation to R&D and number of published papers have recently decreased.
- Citation network analysis revealed reactor safety and fusion as current research trend.
- Nuclear energy research policy will change after Fukushima disaster.

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ABSTRACT

The decision-making process that precedes the introduction of a new energy system should strive for a balance among human security, environmental safeguards, energy security, proliferation risk, economic risks, etc. For nuclear energy, the Fukushima Daiichi nuclear disaster (Fukushima disaster) has brought forth a strong need for transvaluation of the present technology. Here, we analyzed bibliographic records of publications in nuclear science and technology to illustrate an overview and trends in nuclear energy technology and related fields by using citation network analysis. We also analyzed funding data and keywords assigned for each project by co-occurrence network analysis. This research integrates citation network analysis and bibliometric keyword analysis to compare the global trends in nuclear energy research and characteristics of research conducted at universities and institutes in Japan. We show that the Chernobyl accident had only a limited influence on basic research. The results of papers are dispersed in diverse areas of nuclear energy technology research, and the results of KAKEN projects in Japan are highly influenced by national energy policy with a focus on nuclear fuel cycle for energy security, although KAKEN allows much freedom in the selection of research projects to academic community.

1. Introduction

Energy policy is a major social issue beyond the realms of science and requires building consensus between the government and the people. In principle, it is important to publicize the evaluation conditions, methods for collating raw data, and inherent uncertainty in the analysis. However, in reality, even the details of the R&D outlays for energy technology have not been made public. In this light, the concept of *The Science of Science Policy* [1] is of particular interest, especially in the United States, where it was first introduced by Marburger [2], who states "*Science must continually justify itself, explain itself, and proselytize through its charismatic practitioners to gain influence on social events.*" Primarily, this is not a recent concept or approach and has, in fact, been previously used to evaluate technologies such as nuclear energy in the United States. Weinberg [3] proposed the term *trans-scientific* for questions that arise during interactions between science or technology and society since such questions transcend science.

The Science of Science Policy has become a global agenda for academia and government. It is expected to offer intellectual and evidential basis for decision making on science and energy policy. Similarly, in Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) has been planning to launch the *Science of Science, Technology and Innovation Policy Program* [4] since FY 2011 to create a social framework that promotes innovation while assuring citizens of their security and safety and explains the role of science and technology in ensuring safety after the Fukushima incident. The Fundamental Issues

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[*] Corresponding author. Tel.: +81 3 5841 1708; fax: +81 3 5841 1709.
E-mail addresses: kiriyama@pp.u-tokyo.ac.jp, eriko.kiriyama@gmail.com (E. Kiriyama).

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Subcommittee of the Advisory Committee on Energy and Natural Resources pointed out that it is necessary to provide evidences to adopt policy on nuclear energy research in Japan [5].

Energy research and development (R&D) policy plays an important role in accelerating the advancement of energy technologies. The amount of R&D budget is closely associated with the number of patents granted towards energy technologies [6]. Energy R&D investment has also contributed to reductions in the cost of the technologies. Some tools have been used to evaluate energy technology investments and to examine the most effective approaches for evaluating new energy technology [7–9]. Although future cost reduction potential is uncertain, Nemet studied technological learning curves for reducing the uncertainty and improving performance and cost-effectiveness of new energy technologies [9]. Such studies suggest that future models will need to consider other factors such as R&D, knowledge spillovers, and market dynamics; thereby, these studies enable energy technology policy makers to take more realistic decisions about large investments in future energy technologies [10]. Davis and Owens used real option analysis to evaluate investments under uncertainty for renewable energy R&D [11].

However, the Fukushima Daiichi nuclear disaster (Fukushima disaster) has brought forth a strong need to transvaluate the position and historical context of nuclear energy technology and research in modern society. According to the Strategic Energy Plan of Japan approved by the cabinet on June 18, 2010, 53% of the annual electric power supply in 2030 is planned to be supplied from 14 additional nuclear power stations [12].

The present study aims to elucidate the structure of nuclear energy research from both aspects of investment and output of academic research. This research integrates citation network analysis of academic publications with bibliometric keyword analysis of funded projects to compare global trends in nuclear energy research and the trends in academic activities in Japan. The above comparative analysis of academic publications and funded project is designed to clarify and give an overview on, both the input and the output of nuclear energy technology and to investigate the relationships between them.

Recently, several studies have focused on the use of citation analysis in energy research to evaluate the R&D process. For example, Kostoff et al. analyzed the structure of energy research by textual analysis [13,14]. Kajikawa et al. detected a trend of sustainable energy technologies like solar cells and fuel cells [15]. Konur [16] highlighted the importance of scientometrics in gaining valuable insights on the use of algae and other bioenergy sources. Kajikawa and Takeda analyzed the structure and relationships of research in biofuels using bibliometric measures [17]. Liping measured international cooperation in energy R&D in China by bibliometric analysis to determine the frequency of co-publication [18]. Many partial evaluations of nuclear energy have been conducted, but thus far, there have been no comprehensive studies on the field of nuclear energy research. As a partial analysis of nuclear research institutes in Japan, Yanagisawa et al. studied research papers of JAERI (Japan Atomic Energy Research Institute) using bibliometric methods [19,20].

2. Methodology and dataset

We analyzed two types of data: (1) bibliographic records of scientific publications on nuclear energy technology, and (2) funding data on nuclear energy technology in Japan. The former is regarded as output of R&D and the latter as its input. We do not limit the coverage of publication data to publications involving Japanese researchers because they monitor and survey not only previous research in Japan but also that in other countries before starting their own projects.

2.1. Citation network analysis of publication data

We used citation network analysis of publication data to obtain a comprehensive overview of publication data of nuclear energy technology. The data were collected from Science Citation Index-Expanded (SCI-E) compiled by Thomson Reuters, which maintains citation databases covering thousands of academic journals and offers bibliographic database services. SCI-E includes papers published after 1956. We collected bibliographic records of papers published in journals classified as “Nuclear Science and Technology” under the subject category in Journal Citation Reports (Thomson Reuters). In the retrieval, we used the Web of Science, which is a web-based user interface of the citation database. We obtained data from 218,351 papers registered in SCI-E before 29th July 2011. We must notice the limitations of the dataset. One limitation is the noise included in the dataset. Scientific Citations SC of “Nuclear Science and Technology” include publications in the field of pure nuclear science, which can help us understand nuclear science better, for example, as an important means for realizing nuclear fusion and other related issues. Another limitation is the scarcity of publications on nuclear power. In our dataset, publications from the other SC were not covered. For example, publications in several journals on general energy technology, e.g., Journal of Power Sources, Applied Energy, etc., were not included in this dataset.

The collected data were analyzed by citation network analysis. In this analysis, a citation network was created where each paper is a node and every citation is a link. Hence, we eliminated 70,552 papers that have no citation from or to any other papers and included only the data of the largest graph component for further analysis, i.e., 147,799 papers. After extracting the largest connected component, the network was divided into clusters using the topological clustering method [21], which does not need heuristic input parameters. This method discovers tightly knit groups of papers with a high density of links within each cluster. By arranging the citation network into clusters, we can identify research fronts that consist of a group of related papers. In citation network analysis, co-citation and bibliographic coupling has been used; however, in co-citation and bibliographic coupling, core papers are sometimes not included in the largest component, especially immediately after these papers were published [22]. For example, the most cited paper in our dataset, “GEANT4-a simulation toolkit,” which was published in Nuclear Instruments and Methods A in 2003, received 11 citations in 2003 and 181 citations in 2004; whereas, the average publication year of citing papers is 2009. It is plausible that these publications are overlooked when we use co-citation and bibliographic coupling. Therefore, we regard direct citations as links in citation networks.

After clustering the networks, we analyzed the characteristics of each cluster by investigating the titles and abstracts of papers that are frequently cited by the other papers in the cluster, as well as the journals in which the papers in the cluster were published. We named each cluster and listed the keywords for each cluster from the titles and abstracts of the most cited papers in the cluster. The average publication year of papers in each cluster was calculated to know the trends in the research field.

2.2. Term co-occurrence network analysis of funding data

We also studied the structure of R&D in nuclear energy technology by analyzing research funded projects in the KAKEN database [23] from 1972 to 2011. KAKEN (Grants-in-Aid for Scientific Research) is the biggest funding resource for academic research in Japan (as shown in Fig. 1). MEXT and the Japan Society for the Promotion of Science (JSPS), a funding agency of MEXT, offer financial support for KAKEN projects [24]. It should be noted that IEA has published nuclear energy RD&D budgets that include Japan and that MEXT provides data as well. However, it is difficult to analyze the historical transition of R&D in nuclear energy using IEA data because it does not offer detailed topics in nuclear energy projects. Therefore, we limited our analysis to the KAKEN database, which is established and maintained by the National Institute of Informatics (NII) with the support of MEXT and JSPS. We extracted all the projects categorized under nuclear engineering in the KAKEN database.

We then analyzed co-occurrence of keywords in each project and their historical trends. The same steps taken to conduct a citation network analysis of academic publications were used to analyze the structure of funded projects. In co-occurrence network analysis of funding data, keywords assigned for each project are extracted and used as nodes in network analysis. Co-occurrences of keywords in each project were regarded as links. A total of 9686 keywords for 1900 research projects (corresponding to the category of 'nuclear engineering') were extracted from the KAKEN database. Co-occurrence of keywords was calculated for these 1900 projects. Clusters consisting of keywords were then created using the same clustering algorithm. Characteristics of each cluster were judged by using the most frequently co-occurred keywords in that cluster as a clue.

In order to distinguish the contributions made by Japanese researchers, we counted the number of publications in each cluster (#publications by Japanese researchers). We determined the share of publications in each cluster (share of Japan) by dividing #publications by Japanese researchers by the total number of publications in the cluster. In order to determine the relative volume of publications in each cluster, we calculated the cluster share by dividing the number of publications in each cluster by the total number of publications in the super cluster of the selected cluster. For example, the cluster share of the cluster C01 was calculated as the share in the maximum connected component. The cluster share of C01.1, which is a subcluster of C01, was calculated as the share of C01.1 in C01. The share in Japan was also calculated by dividing #publications by Japanese researchers in each cluster by the total number of publications by Japanese researchers. For a given cluster, if the share in Japan larger than the cluster share indicates that Japan focused on that specific research cluster.

3. Results

3.1. Results of citation network analysis

Fig. 2 shows the number of publications by authors in different countries. As shown in Fig. 2, in 2011, Japan was second only to the United States in the number of research papers related to nuclear energy technology. 29,651 publications are from Japan, whereas 64,579 papers are from the United States. The number of publications by Japanese researchers reached its peak around the year 2000, but declined especially in the late 2000s.

After clustering of citation networks, five main clusters were obtained: cluster 1 (C01: 32,103 papers), detectors; cluster 2 (C02: 27,238 papers), irradiation; cluster 3 (C03: 23,546 papers), radiation; cluster 4 (C04: 17,362 papers), lasers; and cluster 5 (C05: 13,530 papers), reactor.

Because it constitutes the basis of nuclear engineering, C05 (reactor) was clustered recursively in order to identify sub-clusters to know the detailed structure of that cluster. Thus, we found that there were mainly six sub-clusters of C05: C05.1 (2040 papers), two-phase flow; C05.2 (1804 papers), corrosion; C05.3 (1708 papers), integral fast reactor; C05.4 (1023 papers), tritium; C05.5 (995 papers), in-vessel; and C05.6 (883 papers), fusion.

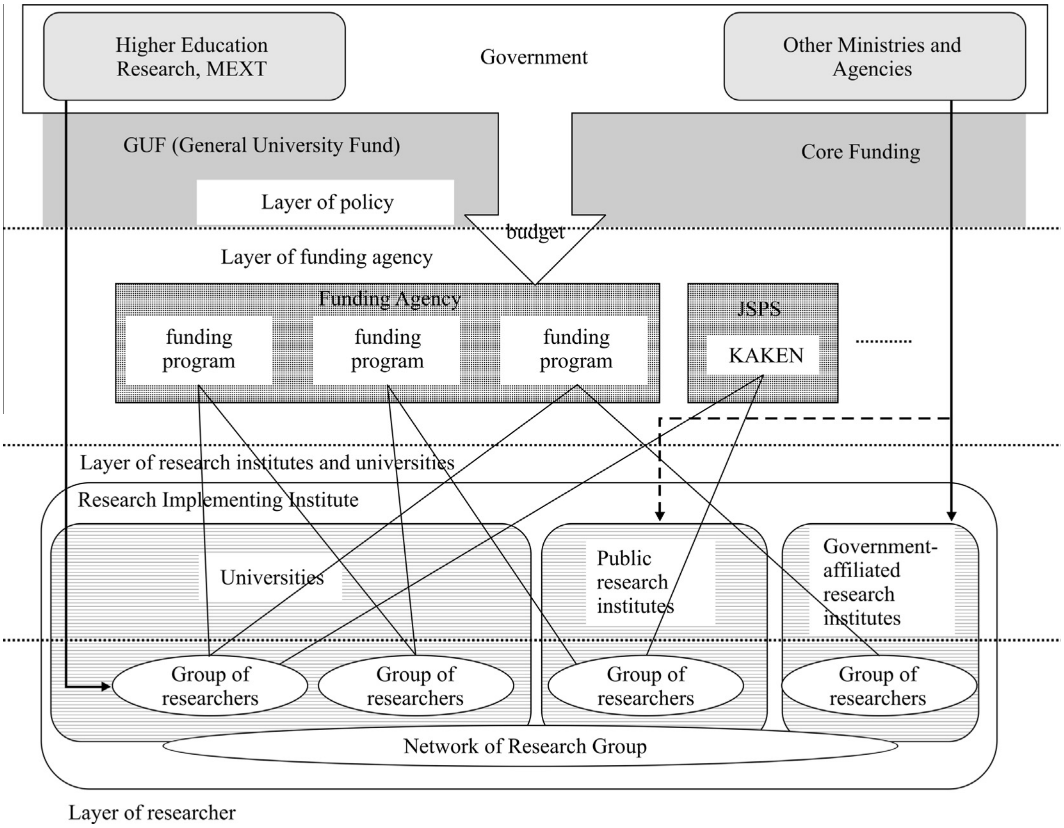

Fig. 1. Funding system in Japan [24].

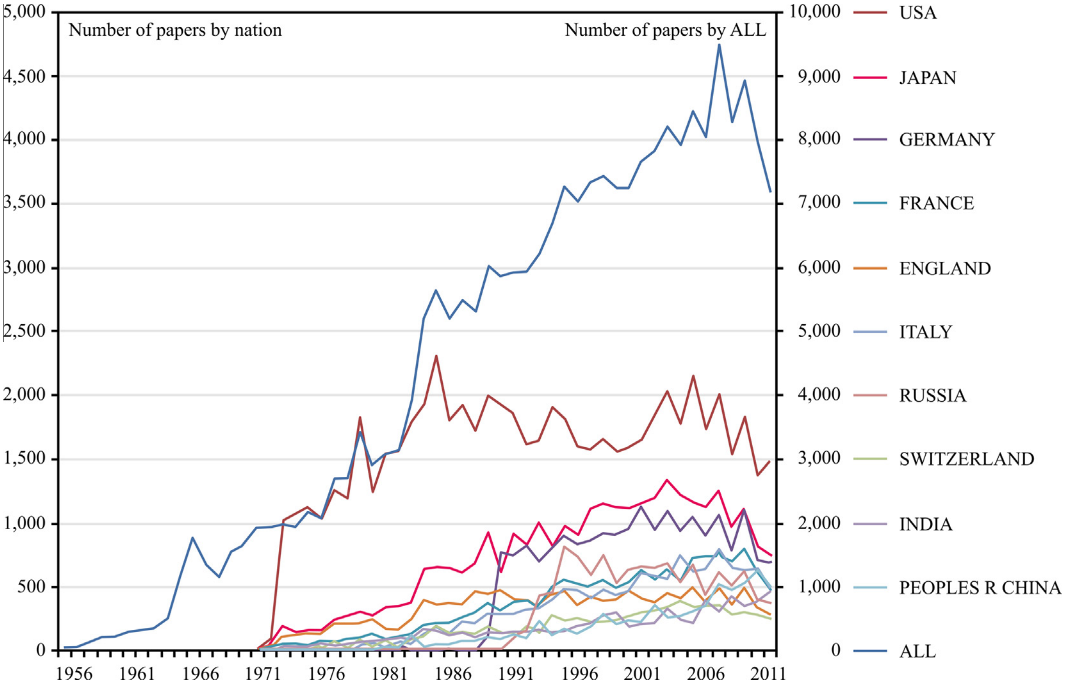

Fig. 2. Number of annual papers of SC on "Nuclear Science and Technology".

3.2. Results of co-occurrence networks analysis

As summarized in Table 1, after clustering co-occurrence networks, 10 main clusters were determined: K 01 (1690 keywords), isotope separation; K 02 (799 keywords), radioactive waste and geological disposal; K 03 (647 keywords), radiation damage; K 04 (319 keywords), two-phase flow; K 05 (274 keywords), nuclear fuel; K 06 (257 keywords), accelerator; K 07 (135 keywords), irradiation; K 08 (118 keywords), stress corrosion cracks; K 09 (111 keywords), heat exchange; and K 10 (110 keywords), actinide.

The above keyword clusters can be further classified into several groups. For example, "isotope separation: K 01" and "nuclear fuel: K 05" have a strong relationship because they are regarded as the front-end of nuclear fuel recycling in the energy policy of Japan, while "radioactive waste and geological disposal: K 02" and "actinide: K 10" are the back-end of nuclear fuel recycling and the MOX fuel of nuclear fuel recycling, respectively. Similarly, four clusters, "radiation damage: K 03", "two-phase flow: K 04", "irradiation: K 07", and "stress corrosion cracks: K 09" are related with the nuclear reactor.

3.3. Trends in global publications and research funded projects in Japan

Table 1 shows average publication year of the papers published in each cluster and the average year of the projects. Because of the nature of the data collected, the average years are different between papers and projects. The number of papers has significantly increased each year; therefore, the average year for each cluster is quite recent. However, the number of projects is rather constant due to the total budget constraint and the average project year becomes older than the average publication year. In addition, it takes several years to publish papers after receiving grants. Therefore, it is not relevant to directly compare the average years of publications and actual publication years. Despite such limitations, the order of average years in each category of data, i.e., papers and projects, among clusters can provide useful implications.

Table 1
Average year of papers and keywords of funded project in each cluster.

Cluster No.	Trends of papers	Average publication year	Cluster No.	Trends of KAKEN keywords	Average project year
C02	Irradiation	1995	K01	Isotope separation	1984
C03	Radiation	1996	K02	Radioactive waste and geological disposal	1985
C04	Laser		K03	Radiation damage	1986
C05	Reactor	1997	K04	Two-phase flow	1986
C05.1	Two-phase flow		K05	Nuclear fuel	1987
C05.4	Tritium		K06	Accelerator	1988
C01	Detector		K09	Heat exchange	1989
C05.5	In-vessel	1998	K10	Actinide	1990
C05.3	Integral fast reactor		K07	Irradiation	1992
C05.2	Corrosion	2001	K08	Stress corrosion cracks	1994
C05.6	Fusion				

Table 2 shows the number of publications by Japanese researchers and the corresponding cluster share. Here, the number of publications by researchers whose affiliations are in Japan (# publications) is shown for five major clusters in the maximum connected component and for six major sub clusters of C05 (reactor). The share of Japan is high in C02 (irradiation) and C05 (reactor) as can be seen in Table 2. Among the sub clusters of C05 (reactor), C05.4 (tritium) is the highest and reaches 46.4%, which means that about a half of papers in C05.4 are from Japan. The share of Japan in C05 (reactor) is larger than 21%.

Cluster share in Table 2 was calculated as the ratio between the number of publications in each cluster and all publications in the citation network, and therefore, it is proportional to the size of each cluster. The share in Japan was calculated as the ratio

Table 2
Number of publications by Japanese researchers and Japan's shares.

Cluster id	Cluster name	#Publications by Japanese researchers	Share of Japan (%)	Cluster share	Share in Japan
C01	Detector	3131	9.80	21.70	16.90
C02	Irradiation	4370	16.00	18.40	23.60
C03	Radiation	1947	8.30	15.90	10.50
C04	Laser	1862	10.70	11.70	10.10
C05	Reactor	2919	21.60	9.20	15.80
C05.1	Two-phase flow	393	19.30	15.10	13.50
C05.2	Corrosion	452	25.10	13.30	15.50
C05.3	IFR	361	21.10	12.60	12.40
C05.4	Tritium	475	46.40	7.60	16.30
C05.5	In-vessel	199	20.00	7.40	6.80
C05.6	Fusion	99	11.90	6.20	3.40

between the number of publications from Japan in that cluster and all publications from Japan in the citation network. Cluster share in Table 2 was the ratio between the number of publications in each sub-cluster and all publications in C05. When the share in Japan exceeds the cluster share, it means that Japan focuses on that cluster more intensively than the rest of the world, on average. As can be seen in Table 2, Japan has actively published papers in C02 (irradiation) and C05 (reactor) but not in C01 (detector) and C03 (radiation). At the sub-cluster level, Japan seems to focus on C05.4 (tritium) but is weak at C05.6 (fusion).

As shown in the Section 3.2, the 10 main clusters of funded academic research projects in Japan are isotope separation, radioactive waste (i.e., geological disposal), radiation damage, two-phase flow, nuclear fuel, accelerator, heat exchange, actinide, irradiation, and stress corrosion cracking (listed in Table 1).

4. Discussion

Because R&D in nuclear energy requires huge investments, commercialization of certain technologies requires long-term political commitment. In order to observe the trends for gaining a better understanding, it will be necessary to examine not only the trends in basic research, but also the extent to which national budgets have been devoted to the field over the years. Compared to the results of citation network analysis of papers that are dispersed in diverse areas of nuclear energy technology research, the results of KAKEN projects were observed to be highly influenced by energy policy with a focus on nuclear fuel cycle. While clusters in citation network of papers include basic fields like detectors and radioactivity of materials, clusters in co-occurrence network of keywords in projects include isotope separation and radioactive waste and geological disposal as major clusters. According to the Long-term Nuclear Program [25], it is important to ensure a stable energy supply in the future by promoting nuclear energy R&D, improving energy security in Japan, and promoting the further development of the society and the economy.

As shown in Table 1, the major themes in nuclear energy research seem to emerge from research into fundamental phenomena such as irradiation and radiation, whose average publication years are rather old compared to those of other paper clusters.

It is noteworthy that even in the early developmental stage, Japan focused on irradiation in reactors rather than radiation of radioactive materials as can be seen in Table 2, in accordance with which, a strong commitment to C05 (reactor) is observed later). Following these clusters, some clusters related to application of nuclear materials emerge. These application clusters include laser (C04), reactor (C05; related to nuclear power plants), and sub clusters such as two-phase flow and tritium. Therefore, we can suppose that research trend shifts from fundamental physics to applications. However, some recent, emerging paper clusters have average publication years that are more recent than those of others, i.e., corrosion (C05.2) and fusion (C05.6). These two clusters seem to aim at opposite directions, i.e., risk management and innovation. Research on corrosion aims to maintain safety of reactors, to understand corrosion behavior of reactors, and to measure corrosion kinetics. Research on fusion is focused on the development of nuclear fusion reactors. The publication trend shown in Table 2 indicates that Japan has relatively less focus in C05.6 (fusion) than corrosion (C05.2) compare to the trend of the world average.

We can see both common and different clusters between paper clusters and project keyword clusters. For example, the corrosion-related clusters, corrosion (C05.2) and stress corrosion cracks (K 08) are the youngest in both paper clusters and keyword clusters. Therefore, reactor safety is emerging in both research and investment. The oldest project keyword cluster is isotope separation, while irradiation is the oldest paper cluster. This implies that while research cluster seems to start from fundamental understanding of nuclear materials, earlier investment is on research to secure nuclear fuel. We compare the above results with the historical trend in events related to nuclear energy. As shown in Fig. 3, after the energy crisis of 1973, nuclear energy received a fillip as an alternative to oil in order to develop energy security in Japan [26]. Then, in 1974, the three electric power laws were promulgated to promote the establishment of nuclear power plants by offering plenty of subsidies for the region where the plant will be constructed [26]. We see that the Japanese research, development, and demonstration (RD&D) budget for nuclear energy increased significantly every year. Similarly, the number of papers in nuclear science & technology also tended to increase.

Next, we focus on clusters 3 and 5 (C03 and C05) to explore the impact of the Chernobyl accident on the former Soviet Union, as shown in Fig. 3. After the Chernobyl accident (in C03), the number of papers containing the keyword "Chernobyl" in keywords and abstract was 417, and the effects of radiation on humans, food, and the environment have been evaluated under uncertainty [28–30]. After careful investigation, we find that some papers in cluster 3 are related to the Chernobyl accident that occurred on April 26, 1986. Moreover, we can see that the proportion of papers published in C03 by Japanese researchers was nearly constant. Further, in C05, the number of papers containing "Chernobyl" in keywords and abstract is 2. Although some research focused on the components of safety issues like corrosion and flow in-vessel, this implies that research on the failure itself and reactor in total system was not adequate. Saji showed that one of the most favorable advantages of a fusion reactor is its safety; its hazard characteristics are such that land contamination equivalent to that experienced in the Chernobyl accident can be physically excluded [31]. These evidences imply that Japan has produced less expertise on the handling of radioactivity and response to nuclear fission accidents. Actually, share in Japan at C03 (radiation) is relatively low (Table 2).

The JCO critical accident at Tokaimura occurred in Japan in 1999. These serious accidents were supposed to lead Japanese people to believe that zero risk is a myth with respect to nuclear technologies. However, the Chernobyl accident seems to have had little impact on basic research and national investment. Even after the Chernobyl accident, there was no change in the increasing research budget. Actually, the average year that projects were adopted for K 08, i.e., stress corrosion cracks, which has a relationship with reactor safety, is 1994, which is more than 10 years after the Three-Mile Island accident and nearly 10 years after the Chernobyl accident. The budget structure reported to the International Energy Agency (IEA) does not include details on decommissioning, environmental protection, plant safety and integrity, and nuclear waste management, which are clearly very important in light of the Fukushima incident.

Previous studies found that governmental R&D budgets were especially larger in US and Japan among the International Energy Agency (IEA) countries [6]. Energy policy is especially important for Japan, which has fewer natural resources to secure energy supply and where nuclear power has been regarded as an indispensable option for energy supply. While investment in energy technologies had been decreasing in the US [6,32], Japan has consistently invested finances in energy R&D [6]. The Atomic Energy Basic Act was partially amended for the first time in 34 years with the intention of contributing to "national security" [33]. Nuclear energy has been considered an indispensable option for mitigating climate change [34].

After the 1997 Kyoto Protocol (COP 3) and the recognition of the dangers of global warming, there was a period of *nuclear renaissance* characterized by renewed interest in nuclear energy as a non-carbon-based energy source. Therefore, nuclear energy, with its unique merits, particularly from the environmental perspective, has become one of the most promising energy options in Japan. The global merit of nuclear energy was also advocated by researchers in other countries. For example, Rashad compared normal operations and accidents in the full energy chain analysis and reported that nuclear power has a potentially prominent role in protecting the global environment owing to the extraordinarily high energy density of nuclear fuel [35]. Besman analyzed historical data of capital investment in nuclear plant construction and reported that nuclear energy usage can reduce GHG emissions and control climate change and thus must be used as a mid-to-long-term strategy [36]. Nuclear energy research in Japan was at its peak in both research output (Figs. 3 and 4) and research input (Fig. 4) around 2000. In Japan, the budget does not increase considerably, and Japan's share of research output remains constant at a high level for several years after COP 3. As shown in Fig. 4, the share of budget is decreasing during the mid-2000s, while the relationship between such a decrease and the Tokaimura critical accident is not clear.

As illustrated in Figs. 3–5 nuclear energy research in Japan showed a trend of securing energy supply and developing own reactors, but this trend was neither influenced nor changed by critical accidents in Three Mile Island (TMI), Chernobyl, and Tokaimura until the mid-2000s. However, it is surprising what happened after Fukushima. According to the IAEA [37], growth in nuclear energy might slow down considerably in the aftermath of the Fukushima incident, although nuclear energy is still important from the standpoint of climate change. However, the situation surrounding nuclear energy technology is not optimistic. Grubler [38] showed that the real construction costs for nuclear reactors increased steadily in France and the United States between 1970 and 2000. He concluded that the potential role of nuclear energy in climate change mitigation could not be assessed seriously because the uncertainties in the anticipated learning curves of new technologies like renewable energy technologies might be much larger than often assumed. On the contrary, nuclear energy includes "negative learning" in which specific costs increase rather than decrease with accumulated experience of fatal accidents.

In Japan, the Cost Verification Committee of the Energy–Environment Council established after Fukushima disaster is responsible for determining the cost of electricity generated by nuclear power plants. However, the committee has not published detailed data. Although case studies for model plants are available, the raw cost data for realistic verification of trends are not available [39].

Choosing future energy technology portfolios requires a socially acceptable risk based review of diverse scenarios. The role of nuclear energy technology should be determined based on a thorough transvaluation of the body of scientific knowledge gathered to date. Moreover, because energy policy decision-makers bear this responsibility, people who have chosen them are also equally responsible. The government should gather a vast amount of reliable data, and scientists should evaluate the data for assessing all the energy technology options available and convey the results to people in the society openly.

Since the Fukushima disaster in 2011, The National Policy Unit (NPU) and the Ministry of Economy, Trade and Industry (METI) have decided to abandon the current plans and re-chart a new

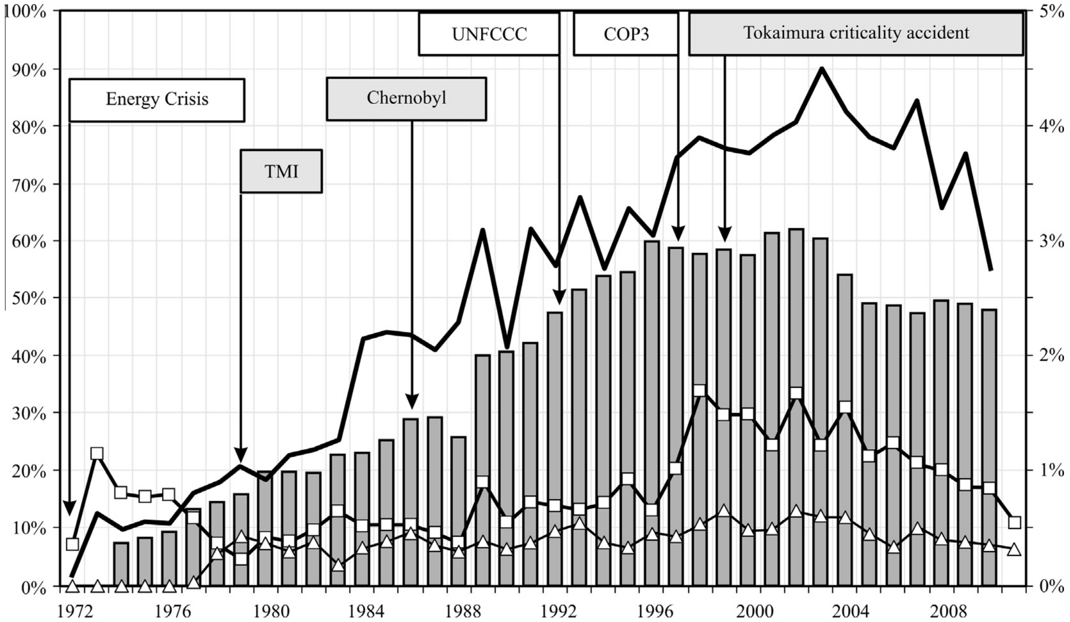

Fig. 3. Budget and paper share in Japan. (Left axis) Proportion of Japanese research papers in the total number of published papers in the World in each year in the field of nuclear science and technology under the subject category in Journal Citation Reports (Thomson Reuters) and in clusters 3 and 5, specifically. (Right axis) Proportion of Japanese research, development, and demonstration (RD&D) budget for nuclear energy per total for OECD countries. (*Source*: ISI and OECD iLibrary [27]). UNFCCC is the United Nations Framework Convention on Climate Change.

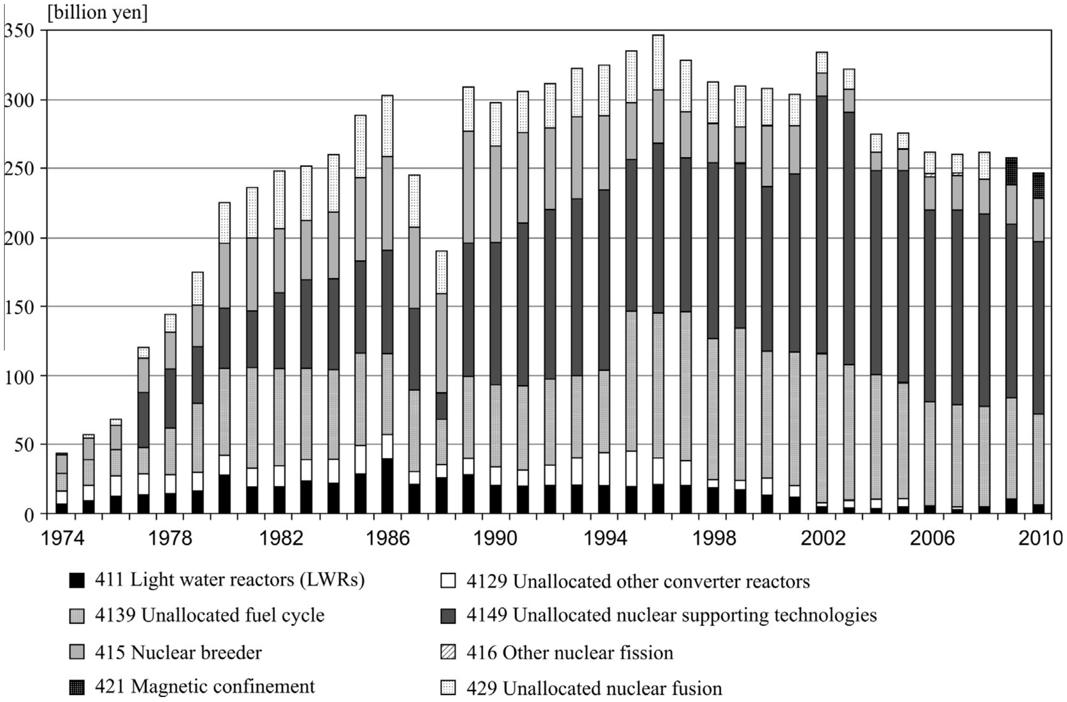

Fig. 4. Japanese R&D budgets for nuclear energy technology options (*Source*: OECD iLibrary [27]).

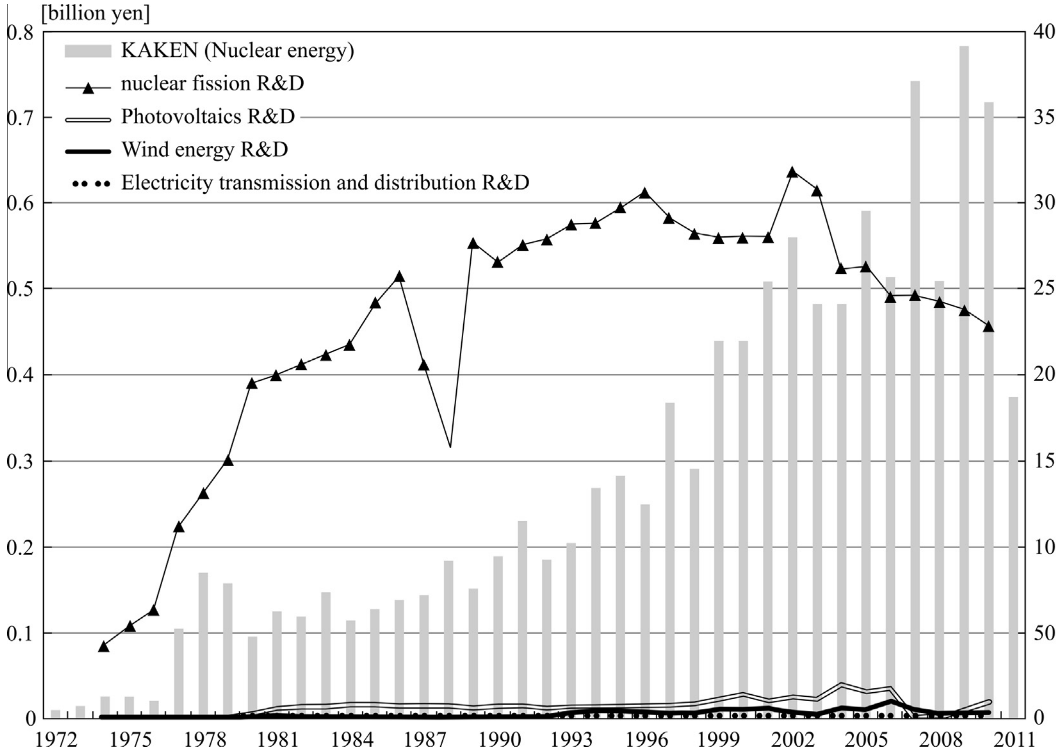

Fig. 5. Japanese R&D budgets for energy technology options (*Source*: KAKEN database [23] and OECD iLibrary [27]) (Left axis) the amount [billion yen] of KAKENHI for nuclear energy or energy in general in each year. (Right axis) the amount [billion yen] of R&D budget for energy technology (nuclear fission, photovoltaics, wind, electricity transmission and distribution) in each year.

Strategic Energy Plan to formulate a new energy mix by close coordination and cooperation with civil society. This new plan aims to reflect public opinion through highly transparent discussions, as reported in the Basic Energy Plan for Japan [40].

The safety requirements for protecting people increased strongly after the severe Fukushima disaster; thus, the capital cost of nuclear power plant construction and the operation cost will have increased considerably, which will diminish its competitiveness.

However, this does not mean that we should completely discard the option of nuclear energy in Japan. The historical importance of nuclear energy in Japan as compared to other sources is reflected in the Japanese energy R&D budgets and KAKENHI funds for nuclear energy, as shown in Fig. 5. Because the amount of RD&D budget for nuclear energy is more than 1000 times the budget amount of KAKEN for nuclear energy or energy in general, it implies that decision-making in energy policy has a significant impact on energy RD&D trends in academic research. KAKEN is a research program where academic researchers can apply with no restriction while the budget on nuclear energy projects in KAKEN is too small compared to the total budget spent for nuclear energy. To borrow an argument from Nemet and Kammen who examined investments in R&D in the energy sector, large government R&D initiatives crowd out other R&D programs [10]. It is straightforward to consider that it is politically difficult to regard such a huge investment made in the past as a sunk cost. Toshinsky et al. note that small power multi-purpose modular fast reactors would enhance competitiveness in the use of innovative nuclear power technology in which natural uranium power potential is used effectively and the intrinsic conflict between economic and safety requirements has been essentially mitigated [41]. Nordhaus notes that the new nuclear power technologies are cited as examples of technologies that are too expensive for markets to fund [42]. Research in this direction might open new possibilities for nuclear energy policy.

Therefore, governmental initiative still plays a significant role in the direction of R&D and advancements in nuclear energy. After the Fukushima disaster, it may be difficult to arrive at an agreement on utilizing nuclear energy as the primary energy supply source of the future in Japan. At the same time, we must distinguish operation from education and research. Even if the operations of the nuclear power plant for energy generation are ceased in Japan, such a move should have no bearing on the need for research and expertise in nuclear energy. There exist necessary activities to manage waste disposal and decontamination [43]. We must also note that the contribution of nuclear science and technology is not limited just to the nuclear power plant [43]. As shown in our analysis, it is strongly connected with basic science for understanding radiation phenomena and developing advanced laser technology, which can be applied to other industrial sectors.

Moreover, scientific knowledge is part of the public domain. The outcome of R&D driven by the initiatives of the Japanese government is not limited only to the domestic stakeholders in Japan [44]. We are obligated to contribute to global environmental safeguards, human security, energy security, proliferation risk, etc., through expertise in nuclear science and technology and related fields. Consequently, the direction of R&D should be governed not by basing it on the significance of the nuclear power plant as an electricity supply option but by comprehending past experience and expertise; the diverse perspectives on domestic issues after the Fukushima disaster; the global environmental, energy, and human security issues; and the responsible contributions and open collaborations for solving such issues.

5. Conclusions

The present paper has outlined that the proportion of the Japanese R&D budget devoted to nuclear energy has generally increased, as has the proportion of research papers in this field from Japan. They peaked around the year 2000 (as shown in Fig. 3). However, very recently, there has been a decrease in the budget allocation, and a similar trend can be seen in the number of papers. Our results obtained by citation network analysis showed that the global trend of research has shifted from understanding basic concepts such as irradiation and radiation phenomena and nuclear fission reactor, to reactor safety and nuclear fusion. However, projects in Japan begin with interest in the nuclear fuel cycle for energy security, which indicates the strong influence of national energy policy on academic research. Moreover, the trend is not influenced by critical accidents such as those at TMI, Chernobyl, and Tokaimura, even as we see a recent decline in both R&D inputs and outputs in Japan. The shift from understanding the basic concepts to nuclear fission can also be seen in the projects in Japan. This shift might be related to Yanaihara Principle for Nuclear Research prohibiting government budget allocation to Japanese universities for research on nuclear fission, except for KAKEN and nuclear fusion. Yanaihara Principle was settled in 1955 but was substantively reconsidered after 2000 similar to the Act on Special Accounts for Electric Power Development Acceleration Measures. We think that this trend will change after the Fukushima disaster because the trend of research is driven by energy policy. Reflecting the current situation, research and talents in decontamination, decommissioning, and regulation are necessary. Scientists and policymakers reconfirm transparency, openness, and accountability to gain public understanding and trust in the decision-making process for energy technology policy in Japan. It is necessary to accurately assess the pros and cons—risks, benefits, costs, economic potential, environmental impact, etc.—of all the energy technology options available when presenting these options for people. Nuclear energy policy in Japan is apparently at a turning point.

One of the directions it might take would be to focus on reactor safety, decommissioning, and on emerging research like small power modular reactors. What now needed to do for people is energy and environmental technology assessment in order to go beyond Fukushima disaster, scientists committed to energy researches should overhaul the state of science through restructuring the vulnerable aspects exposed even by our analysis.

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