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Review

Sustainable Decommissioning Strategies for Nuclear Power Plants: A Systematic Literature Review

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Abstract: The decommissioning of nuclear power plants (NPPs) is rapidly increasing because NPPs are not only no longer profitable in many cases but are also being decommissioned due to a lack of public acceptance or political reasons in many countries, particularly in Europe, following the explosion of the Fukushima Daiichi NPP. Accordingly, a significant body of research has focused on achieving safe, environmentally sound, and sustainable decommissioning in many countries where there is demand for NPP decommissioning. In order to achieve sustainable decommissioning that restores the NPP site to its pre-NPP environmental state, it is necessary to understand the safety, technology, and cost aspects as well as having the process and strategy to systematically promote them. Although there are a limited number of countries with experience and knowledge in the management of decommissioning multiple NPPs, researchers in countries just starting NPP decommissioning need diverse research information on how to formulate a sustainable decommissioning strategy as well as related factors. In particular, a systematic review of decommissioning strategies, such as DD, ID, and ET, and the influencing factors associated with each strategy is needed from the researcher's point of view. In this regard, this study reviews the research literature on decommissioning strategies for nuclear power plants with a sustainable perspective. A systematic method involving a meta-analysis is used. The results of this study confirm that many researchers are most interested in DD and are dealing with ID and ET at the same level, but in reality, DD and ID are being adopted at similar rates. Thus far, only three ETs have been adopted in the United States. Most countries that have adopted ID are deemed to have been influenced by political decisions.

Keywords: sustainable decommissioning; nuclear power plant; strategy; social impact; systematic literature review

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1. Introduction

Nuclear power plants (NPPs) produce more than half of America's carbon-free electricity due to their superior reliability, enormous clean-air compliance value, and large capacity for power generation [1]. Due to these advantages, as of 31 December 2020, 442 reactors were in operation worldwide, and 52 reactors were under construction [2].

The international nuclear and radiological event scale (INES) has seven levels, where which levels 1–3 and 4–7 are called 'incidents' and 'accidents', respectively [3]. The descriptions of the levels are as follows: level 1—anomaly, level 2—incident, level 3—serious incident, level 4—accident with wider consequences, level 5—accident with wider consequences, level 6—serious accident, and level 7—major accident. Since the Shippingport NPP in the USA started its operation in 1957, NPP accidents have been classified according to the INES classifications as follows: Chernobyl in the Soviet Union (level 7), Fukushima Daiichi in Japan (level 7), Three Mile Island in the USA (level 5), and Saint-Laurent in France (level 4) [4]. Additionally, a critical nuclear accident occurred at the Tokai factory, Japan (level 4). The Chernobyl and Fukushima Daiichi NPP disasters caused a lot of casualties and property damage.

The cost of decommissioning based on the International Structure for Decommissioning Costing can be described by eleven principal activities, as follows: (1) pre-decommissioning actions; (2) facility shutdown activities; (3) additional activities for safe enclosure or entombment; (4) dismantling activities within the controlled area; (5) waste processing, storage, and disposal; (6) site infrastructure and operation; (7) conventional dismantling, demolition, and site restoration; (8) project management, engineering, and support; (9) research and development; (10) fuel and nuclear material; and (11) miscellaneous expenditures. Each activity incurs labor costs, capital/equipment/material costs, expenses, and contingencies.

The cost for each activity differs among nations and among sites in the same country. The cost is not dependent on the size of the NPP. In the USA, the total cost of decommissioning, including site remediation, is in the range of 300 to 840 million USD per unit (2013 value). The cost of decommissioning for Kori unit 1 in Korea was estimated to be 800 million USD.

Once a nuclear facility ends its life, decontamination and decommissioning (D&D) of the facility should be considered. Nowadays, decommissioning strategies involve immediate dismantling, deferred dismantling, and entombment. The stages after the shutdown of a nuclear facility for decommissioning include (1) safe enclosure preparation (site preparation and initial dismantling), (2) a safe enclosure period (updated final decommissioning plan, surveillance, and maintenance), and (3) the final stage (final dismantling, final survey, and license termination).

The decommissioning process must be well planned and optioneered to allow safe and successful completion. This requires interactive processes between the operator, regulator, and other stakeholders. The regulatory body needs to be informed of plans, and project documentation submittals and reviews are essential. The shutdown of a facility should be safe, so surveillance and maintenance programs are necessary. Facilities, including nearby sites, should be characterized, and a detailed plan, including engineering, should be set up. The plan should include health and safety, quality assurance, waste management, project management, permitting and procurement, safety analysis, project baseline, emergency, and training components. After the decommissioning process has been finished as planned, a final survey of the site is performed.

Globally, 192 reactors have been permanently shut down, and 158 reactors are in the decommissioning process or have a decommissioned status [1]. The decommissioning of NPPs is rapidly increasing because NPPs are no longer profitable in many cases. In addition, decommissioning can occur due to a lack of public acceptance or political reasons in many countries, particularly in Europe, following the explosion of the Fukushima Daiichi NPP [5]. To guarantee public safety while conducting sustainable decommissioning, various factors, including economic, technological, and social impacts, should be considered to establish strategies, and related decisions should be made. In order to establish sustainable decommissioning strategies, a wealth of relevant knowledge and experience is needed. The USA has a lot of experience and knowledge in this area, as it has decommissioned nine NPPs, and currently, 19 NPPs are under decommission [6]. However, countries that have just started decommissioning need a variety of information to ensure sustainable decommissioning is carried out. In many previous studies, information and procedures in relation to nuclear-decommissioning strategies have been proposed [7–14], and a significant amount of research has been conducted in various areas. In addition, research has been focused on sustainable decommissioning that is guaranteed to be safe and environmentally sound. In this regard, systematic reviews with up-to-date information are needed so that persons and researchers in charge of establishing a sustainable decommissioning strategy for NPPs can acquire information quickly. Although a large number of review articles have been published in relation to NPP decommissioning, most are reviews related to nuclear engineering and technology rather than being literature reviews of sustainable decommissioning strategies [15–21]. After surveying a literature database related to nuclear engineering, it was concluded that there are also no systematic review articles involving a meta-analysis of sustainable decommissioning strategies. Thus, in this study, we review the research literature on decommissioning NPPs from a sustainable perspective using a systematic method with a meta-analysis. The results of this review research will be used to propose a research direction for the achievement of safe, economical, and sustainable nuclear decommissioning in the future.

2. Sustainable Decommissioning Strategy of NPPs

Since its first mention by the Roman Club in the 1972 report 'The Limits to Growth', sustainability has been considered in a variety of areas, including human activities, economics and management, climate and environment, and national policy [22,23]. Sustainability can be defined in many ways. We present some of the typical definitions in relation to sustainable NPP decommissioning. First, 'Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment' [24]. In the charter for the UCLA Sustainability Committee, sustainability is defined as 'the integration of environmental health, social equity, and economic vitality in order to create thriving, healthy, diverse, and resilient communities for this generation and generations to come. The practice of sustainability recognizes how these issues are interconnected and requires a systems approach and an acknowledgement of complexity' [25]. In the Oxford dictionary, sustainability is defined as 'the ability to be maintained at a certain rate or level' [26].

Reflecting on these definitions, sustainable decommissioning of NPPs involves the restoration of the NPP site and the surrounding environment to its pre-NPP state to promote the health and prosperity of the present and future generations. That is, after NPP decommissioning, hazardous substances harmful to human health and nature in the site and the surrounding environment must be maintained below the pre-NPP level. Although each NPP site has its own requirements, the following principles should be considered in the implementation of sustainable decommissioning: (a) the participation of surrounding community members and other external stakeholders in the decision-making process; (b) the application of integrated, long-term thinking; and (c) the viewing of all parts as potential assets and the creation of a post-decommissioning vision [27].

A strategy is a general plan that is used to achieve one or more long-term or overall goals under conditions of uncertainty [28]. Thus, the sustainable decommissioning strategy for NPPs can be defined as a long-term plan to implement sustainable decommissioning of NPPs. Strategies are important because the resources available to achieve goals are usually limited. A strategy generally involves setting goals and priorities, determining actions to achieve the goals, and mobilizing resources to execute the actions [29]. A strategy can be purposeful or can emerge as a pattern of activity as the organization adapts to its environment or competition [29]. It can involve activities such as strategic planning and strategic thinking [30]. A successful decommissioning strategy for NPPs requires clear direction, a defined end point, planning time, upfront resources, investment, and communication [31]. The best technical and engineering solution can be worthless if it is not a financially, socially, and politically acceptable way to deliver the selected decommissioning strategy while achieving the selected end state [31].

According to literature published by many international organizations, the three main decommissioning strategies are 'immediate dismantling (ID)', 'deferred dismantling (DD)' or 'safe enclosure and entombment (ET)' [6–9,32]. These are the top strategic decision-making strategies, and, to determine which to use, many factors from the following three categories should be reviewed: (a) policy and socio-economic factors; (b) technological and operational factors; and (c) long-term uncertainties [32]. The International Atomic Energy Agency (IAEA) proposed that the following seven general factors should be considered when selecting a decommissioning strategy [8,9]: (1) the national policies and regulatory framework; (2) financial resources/cost of implementing a strategy; (3) spent fuel and waste management system; (4) health, safety, and environmental impacts; (5) knowledge management and human resources; (6) social impacts and stakeholder involvement; and (7) suitable technologies and techniques. Y.A. Suh et al. [7] added reactor and site characteristics, which were introduced in the report from the European Commission [33] as the eighth factor.

For sustainable decommissioning of NPPs, the appropriate strategy, either DD, ID, or ET, should be decided after sufficiently considering the above eight factors. In order to successfully carry out the strategy, a detailed plan, including the budget, technology, manpower, and schedule, should be established. In the current study, the authors conducted a systematic literature review after examining the literature published in this area so far. We focused on the three above-mentioned top strategies and eight general factors.

3. Methods

We searched for articles on NPP sustainable decommissioning strategies in Science Direct, the Web of Sciences (WoS), Taylor and Francis Online, Springer Link, and the Willey Online Library. In the Willey Online Library and the Web of Sciences (WoS), we searched articles published in all journals corresponding to the Science Citation Index Expanded (SCIE) classified by the Institute for Scientific Information (ISI). We searched articles published in SCIE journals in the field of Engineering and Technology in Taylor and Francis Online, Chemistry, Engineering, Material Science, and Physics in Springer Link, and Physical Sciences and Engineering in Science Direct.

The literature was searched sequentially in the aforementioned literature database using the following keywords: nuclear, nuclear decommissioning, and nuclear-decommissioning strategy. Since the nuclear-decommissioning strategy discussed in this review article is a very specific topic, most literature was retrieved from the databases. Google Scholar was used only for the search of literature sources such as books, magazines, and dissertations that could not be found easily in the above databases or for which the original copy could not be downloaded from the above databases.

Out of the records searched, as of 30 December 2021, 1471 records were selected, as shown in Figure 1. This excludes records that were not related to the topic of this study, as well as duplicate records. After removing 324 duplicated records, a total of 302 full-text articles were selected. We excluded 537 records that were not related to nuclear-decommissioning work and 308 that were not related to strategy. Thereafter, 183 articles that were not closely related to the eight general factors mentioned in Chapter 2 were removed. Accordingly, 119 articles related to the eight general factors were targeted for the quantitative and qualitative analyses, and the decommissioning strategies that are performed in each nation were compared. Finally, future research directions to establish a sustainable NPP decommissioning strategy were proposed.

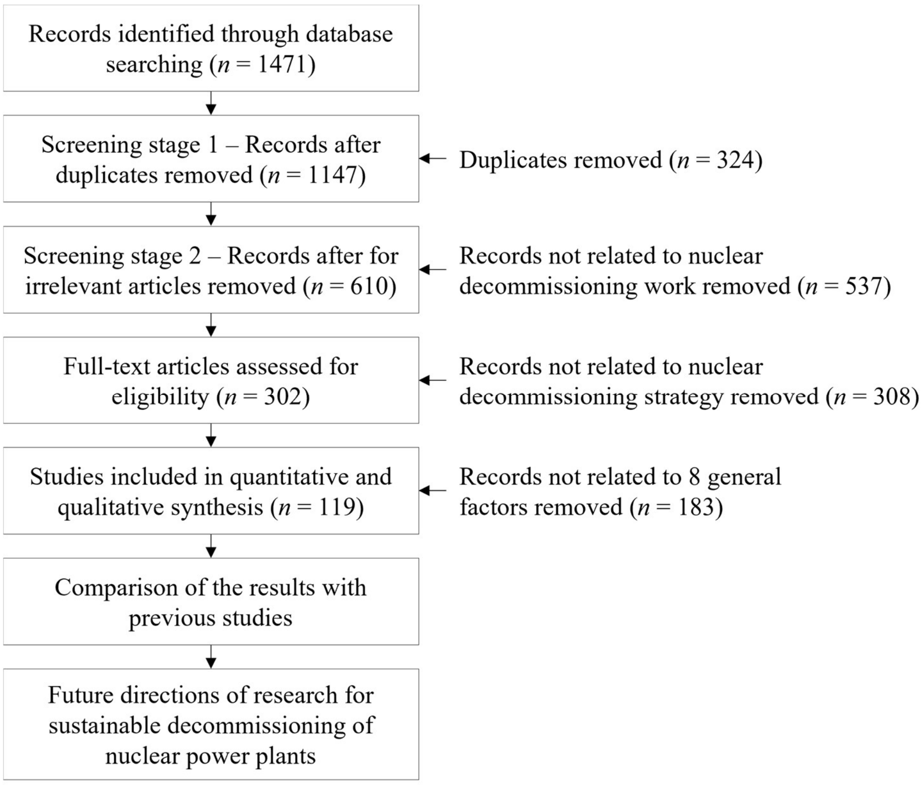


Figure 1. Flow diagram of the literature review and analysis process. (Source: authors' research results).

4. Descriptive Analysis

Nuclear decommissioning requires the use of technology with a high level of difficulty. Thus, thorough preparation and strategies are needed [34]. Decommissioning takes more time than building an NPP, and more waste is produced at once than that produced during operation [35]. To perform nuclear decommissioning in a safe, economical, and eco-friendly manner, decommissioning strategies should be established according to the NPP type and characteristics, and then highly advanced technologies, including decontamination technology, remote cutting and management technology, waste treatment technology, and environment recovery technology should be secured.

Up until now, research in the nuclear-decommissioning field has focused on various areas such as decommissioning costs and technology, radioactive waste management, and treatment and environmental impact assessments. However, compared with research on decommissioning strategies, most studies were focused on a narrow and in-depth level of studies [36,37] to specifically realize the aforementioned eight factors [7–9].

As mentioned in Chapter 2, which of the main decommissioning strategies, ID, DD, and ET, to be used is chosen by considering various factors such as national policies, financial resources, the waste management system, the environmental impact, social impacts, and suitable technologies [15,38–46].

The most suitable strategy should be established by considering the type and characteristics of the NPP and the standpoint of the nation it is located in after analyzing the relationships among the main decommissioning strategies and the eight sustainable nuclear-decommissioning factors or their subfactors. After integrating and analyzing the relationships among the main decommissioning strategies and impact factors through the literature search, no articles with proposed decommissioning strategies were found. Thus, related studies should be continued. In this research, a systematic literature review (SLR) of 119 articles was conducted, as presented in Figure 1, to support related studies.

Table 1 presents the 119 included articles by the country of the main author. South Korea has produced the largest number of papers (25), followed by Russia with 23, Germany with 12, the UK with 9, the USA with 8, and Japan with 7. Eight nations, including China, have published two to six papers. Finally, eight nations, Canada, Italy, Iraq, Switzerland, Sweden, Belgium, Denmark, and South Africa, have published one paper. Two nations, including Slovakia, have published three papers. Four nations, including Austria, have published two papers. Eight nations, including Canada, have published one paper.

Table 1. Number of paper produced by country (Source: research results).

Country	Articles	References	Remarks
South Korea	26	[7,42–44,47–68]	
Russia	23	[46,69–90]	
Germany	12	[13,34,39,91–99]	
UK	9	[16,100–107]	
USA	8	[15,36,45,108–112]	
Japan	7	[14,113–118]	
China	6	[108,119–123]	
Spain	5	[124–128]	
Austria, Slovakia, Taiwan	9	[35,129–136]	3 papers each in three countries
Czech Republic, Brazil, Lithuania	6	[41,42,137–140]	2 papers each in three countries
Canada, Italy, Iraq, Switzerland, Sweden, Belgium, Denmark, South Africa	8	[37,38,141–146]	1 paper each in eight countries
Total	119		

As of October 2021, there were 441 nuclear reactors in operation in 30 countries around the world [147]. More specifically, in the US, France, China, Russia, Japan, and South Korea, there were 93, 56, 51, 38, 33, and 24 nuclear reactors in operation, respectively. The USA has decommissioned nine NPPs and is decommissioning a further 19 NPPs [6]. The 'Nuclear Power Reactors in The World' published in 2021 by the IAEA disclosed that Germany, the UK, Japan, and France had decommissioned or were decommissioning 29, 26, 22, and 10 reactors, respectively [2]. While major NPP-leading nations have decommissioned or are decommissioning many reactors, the literature data on decommissioning strategies in the articles presented in Table 1 are scarce. The reason for this is that these NPP-leading nations had experience with the decommissioning of nuclear reactors and secured technology independently. We also verified that advanced research on technologies to strengthen the safety, efficiency, and ecofriendliness of such operations is actively underway for commercial purposes. Since NPP decommissioning technology is related to business strategy and know-how, leading decommissioning nations are reluctant to disclose academic presentations about key technologies.

Because South Korea has focused on the construction, operation, and lifetime extension of NPPs, its related technologies are at the world's top level. However, South Korea lacks decommissioning technology in comparison to other leading NPP decommissioning nations, which is why a lot of research is underway to secure key decommissioning technology. Despite South Korea being at an early stage in the decommissioning of two reactors, it published the most closely related articles on the topic of decommissioning strategies, as exhibited in Table 1. It is said that Russia has decommissioned or is decommissioning four reactors, but no accurate information is available [2]. However, it is assumed that a large number of articles on decommissioning have been published, since *Atomic Energy*, the oldest journal in the nuclear energy field, is based in Russia. Finally, at the time that the research was conducted, China was operating 50 reactors and had 13 under construction, but there were no reactors undergoing the decommissioning process [2]. Thus, there were few articles on the decommissioning strategy from China, as presented in Table 1, but we expect China to have many NPP decommissioning cases. As a result, we predict that China will actively research to prepare for this.

Figure 2 shows an analysis of the 119 articles by year. The number of nuclear-decommissioning-related papers increased rapidly, with two papers published from 1988 to 1991 (1.7%), 12 papers from 1992 to 2001 (10.1%), 30 papers from 2002 to 2011 (25.2%), and 75 papers from 2012 to 2021 (63.0%). Since commercial power generation using NPPs started in the 1950s, research on nuclear decommissioning has been conducted in advanced nuclear-decommissioning nations, such as the USA and Germany, and this included the early days of the arrival of the shutdown of nuclear facilities. After the 1970s, a large number of countries constructed NPPs, and when the shutdown arrived in the 2000s, related research suddenly increased in South Korea and Japan, where the security of NPP decommissioning technology was urgently needed. In particular, it was verified that research on the technical upgrade of nuclear decommissioning has increased since the Fukushima Daiichi nuclear accident. It is predicted that the increasing trend in the number of published articles shown in Figure 2 will accelerate if research on the technical upgrading of nuclear decommissioning is conducted in China, India, Japan, and Russia—areas with planned construction or current construction of large-scale NPPs.

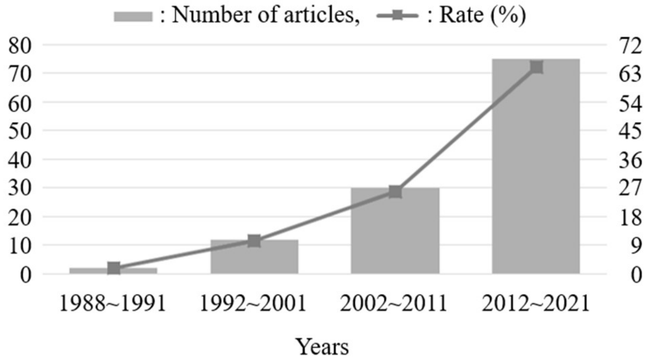


Figure 2. Number of published articles by year (Source: research results).

5. Results and Discussion

5.1. Results of the Quantitative and Qualitative Review

5.1.1. Summary by Adopted Decommissioning Strategy

In the reference data from the IAEA, decommissioning strategies are categorized into four types: immediate dismantling and removal of all radioactive materials (ID), deferred dismantling and placing all radiological areas into a safe enclosure (DD+SE), deferred dismantling, including partial dismantling and placing remaining radiological areas into a safe enclosure (DD+PD+SE), and in situ disposal (ISD), involving the encapsulation of radioactive materials and subsequent restriction of access [2]. This shows that decommissioning strategies can be subcategorized according to political concerns, safety or environmental requirements, technical considerations, local conditions, or financial considerations. However, most articles generally classify the three main decommissioning strategies as ID, DD, and ET.

Table 2 presents a summary of the relevance of nuclear-decommissioning strategies in terms of their use in the 119 articles, as determined by the PRISMA flow diagram shown in Figure 1. As presented in Table 2, DD was mentioned in 117 out of a total of 119 articles (98.3%), while ID and ET were mentioned in 61 articles (51.3%) and 60 articles (50.4%), respectively, resulting in a total of 238 mentions. This result verifies that nearly all articles mentioned DD, whereas ID and ET were mentioned similarly. The number of articles was

119, in which DD, ID, and ET were mentioned 239 times. This means that DD, ID, and ET were mentioned simultaneously in many articles. This means that the subject of the above articles was related to more than one decommissioning strategy.

Table 2. Summary by the adopted decommissioning strategy (Source: research results).

Description	Articles	References	Ratio (%)	Remarks
Deferred dismantling (DD)	117	[2–61,69–88,91–102,108–110,113–117,119–122,124–126,129–133,137,141–144]	98.3	Ratio for 119 articles
Immediate dismantling (ID)	61	[6–8,10,12–16,21,27–29,31,35–37,54–56,58,59,69–88,95–98,103,109–113,116,117,119,121,122,132,137,142]	51.3	
Entombment (ET)	60	[1,6–8,13–16,21,27–29,31,35–37,69–71,73,74,85–122,128]	50.4	

For DD, which was mentioned in most articles, decommissioning takes a long time, around 60 years, but radioactivity is reduced by spontaneous decay during that period. Thus, radioactive waste is dramatically reduced compared to when ID is used. DD also has the advantage that it can significantly reduce the probability of occupational exposure compared with ID. On the other hand, DD has drawbacks, such as difficulty in maintaining the same personnel until the completion of decommissioning, an increase in maintenance and safety management costs, and a delay in site reuse, as it takes a long time [8,9,41,44,45,79,113,116,137].

ID takes around 15 years for decommissioning, which allows the use of consistent personnel and reduces the decommissioning cost compared with DD. It also has the advantages of possible decommissioning schedule prediction and fast site reuse. On the other hand, ID has a high probability of occupational exposure compared with DD and must involve the use of additional shielding and remote control equipment [8,9,40,43,48,49,53,69,72,77,115].

ET is a method with no concern about the residual activity as facilities are completely sealed using concrete without the complete removal of radioactive materials. Here, the sites are considered a kind of waste disposal [8,9,57,74,81,98,110,117].

According to the reference data from the IAEA, 158 reactors were going through the decommissioning process or had been decommissioned in 19 countries as of 31 December 2020. DD was selected for the decommissioning of 72 reactors in 12 countries, as presented in Table 3.

Table 3. Decommissioning strategy used for reactors going through the decommissioning process and already decommissioned reactors (Source: research results).

Decommissioning Strategy	No. of Reactors and Ratio		No. of Countries	Remarks
	No. of Reactors	Ratio (%)		
Deferred dismantling (DD)	72	45.6	12	Dd + PD + SE 46 Dd + SE 26
Immediate dismantling (ID)	60	38.0	13	ID
Entombment (ET)	3	1.9	1	ISD
Others	23	14.5	7	None of the above
Total	158	100.0	19	

ID has been adopted in 13 nations to decommission 60 reactors, and ISD, which involves entombment, has been adopted in the USA for the decommissioning of three reactors. As presented in Table 2, DD has been academically discussed the most, while ID and ET have been studied at nearly the same rates. However, ID has been adopted less often than DD, as indicated in Table 3. However, practically, it has been adopted at a much higher rate than ET. Major nations that have adopted DD (Table 3) are Bulgaria, Canada, Japan, the UK, and the USA, while major nations that have adopted ID are France, Germany, Italy, the USA, and South Korea. If we investigate the data shown in Table 3 in more detail, we can see that national policy and socio-economic factors, which reflect public opinion, played major roles in the adoption of decommissioning strategies for reactors in countries where ID has been used. Note that ISD, which belongs to the ET category, has only been adopted in the USA.

5.1.2. Summary of the Eight Influencing Factors

A decommissioning policy is a set of established goals or requirements for the safe, effective, and efficient decommissioning of nuclear facilities. A decommissioning strategy is the means for achieving the goals and requirements set out in the national policy for the decommissioning of nuclear facilities [9]. However, selecting a sustainable decommissioning strategy is a difficult problem in which many factors are intertwined, as mentioned in Chapter 2. In this study, eight factors are proposed that should be considered when selecting a sustainable decommissioning strategy. These were chosen after investigating the IAEA [8,9] and other articles [7,33]. In addition, the relationships of the 119 articles with the eight factors were studied, as summarized in Table 4.

Table 4. Summary by the eight influencing factors (Source: research results).

Factors	Articles	Ratio (%)	Remarks
Policies and regulatory framework (F1)	15	12.6	Ratio for 119 articles
Financial resources/Cost of implementing a strategy (F2)	28	23.5	
Spent fuel and waste management system (F3)	36	30.3	
Health, safety, and environmental impact (F4)	44	37.0	
Knowledge management and human resources (F5)	5	4.2	
Social impacts and stakeholder involvement (F6)	14	11.8	
Suitable technologies and techniques (F7)	25	21.0	
Reactor and site characteristics (F8)	9	7.6	

The analysis results show that the number of articles related to ‘Health, safety, and environmental impact’ was 44 (37.0%) out of the 119 studied articles, making this the most commonly mentioned factor. This was followed by ‘Spent fuel and waste management system’ with 36 articles (30.3%), ‘Financial resources/Cost of implementing a strategy’ with 28 articles (23.5%), ‘Suitable technologies and techniques’ with 25 articles (21.0%), ‘Policies and regulatory framework’ with 15 articles (12.6%), ‘Social impacts and stakeholder involvement’ with 14 articles (11.8%), ‘Reactor and site characteristics’ with 9 articles (7.6%), and ‘Knowledge management and human resources’ with 5 articles (4.2%), as presented in Table 4. Table 4 verifies that the eight factors are related to one another in the 119 articles in a duplicate manner because the sum of F1 to F8 is 176. This means that not only one factor was studied, but multiple factors were related in many articles according to the NPP type and characteristics.

The results shown in Table 4 indicate that studies in relation to F4 were the most common, followed by those that mentioned F3. The results verified that the foremost considerations had been the reduction of occupational exposure, blocking radioactivity leaks, and safety improvements during decommissioning, as shown by the focus on F4 [44,46,48,50,57,69,87,95,97]. In order to do this, the following studies were actively conducted on the development of decontamination technology to safely remove only radioactive materials [46,57], technology to remotely cut and handle high-radioactivity facilities [50,91], technology to safely handle various types of waste produced during decommissioning processes [59,95], and recovery technology to restore contaminated facilities and sites to their original states [49,87]. It was also shown that these detailed technologies are mutually and organically related to safe and efficient decommissioning processes.

We verified that radioactive waste produced during decommissioning for F3 could cause serious damage that cannot be recovered in the future if it is not systematically managed, so this aspect was provided priority [36–38,63,67,71–73,108,113,145,148]. For advanced decommissioning nations, such as the USA, France, and Germany, technologies to handle concrete and metal waste, which accounts for most of the dismantled waste, have reached the commercialization level [108,113], and radioactive waste is reused in various areas, including in NPPs, through the deregulation of radioactive waste [75,76]. However, their safe handling methods are not secured for some specialized waste, so the waste is temporarily stored, and studies on how to handle this are currently underway [62,138].

As such, the related articles tell us that decommissioning strategies that are suitable for NPP types and characteristics should be established and prioritized to allow nuclear decommissioning to be performed in a safe, economical, and eco-friendly manner. After this, suitable decommissioning technologies for decommissioning, remote cutting and handling, waste treatment, and environmental recovery should be secured according to the adopted decommissioning strategy; that is, suitable decommissioning strategies should be established and prioritized with consideration of the nation, region, and environment, and F1 to F8 in Table 4 should be fully considered.

5.2. Co-Occurrence Network Analysis

In Section 5.2, nuclear-decommissioning strategies and the eight general factors adopted in articles were analyzed in terms of each strategy's adoption process. When using the analyzed results, VOSviewer software was used to conduct a co-occurrence network analysis. The subfactors of the eight general factors were also analyzed in the article keywords. For reference, the subfactors included policy, commercial issues, spent fuel, health and safety, knowledge management, social impacts, technologies and techniques, reactor and site characteristics, the regulatory framework, the waste management system, the environmental impact, human resources, and stakeholder involvement. As a result, a network between the index keywords was generated, as shown in Figure 3.

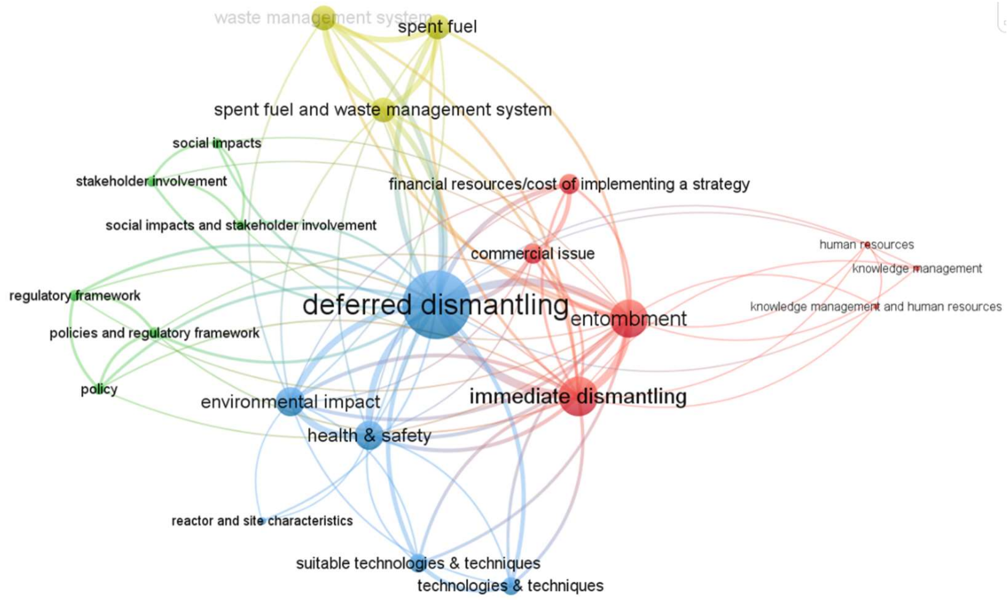
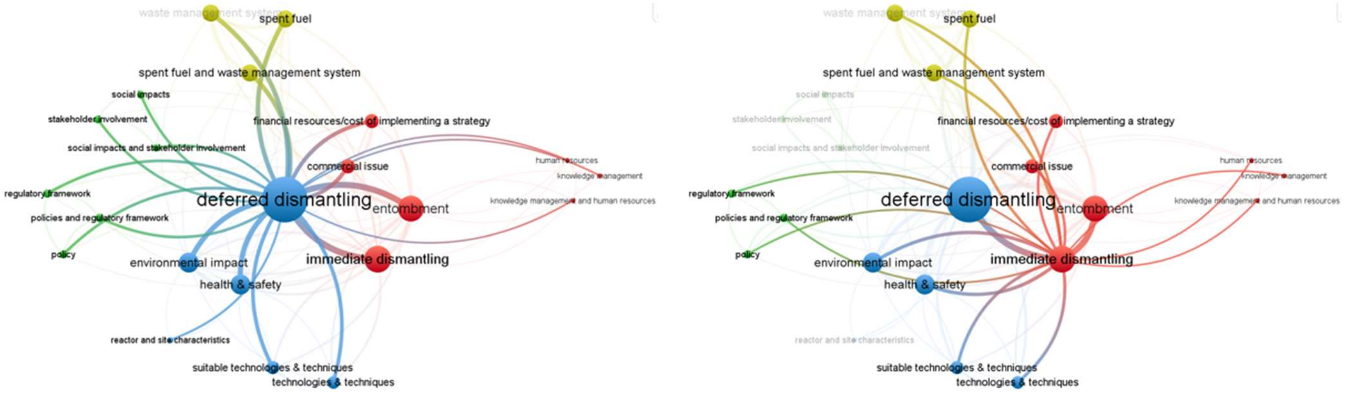


Figure 3. Results of the co-occurrence network analysis.

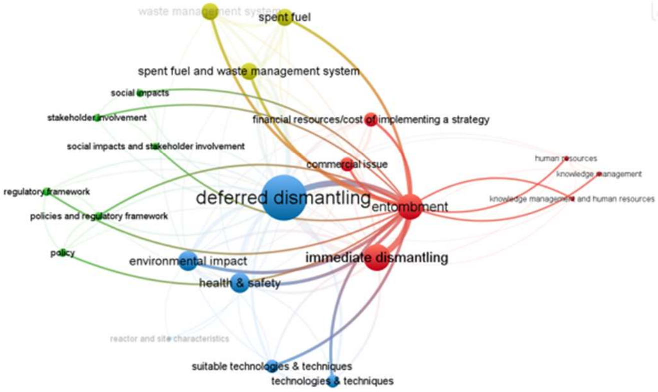
The thicknesses of the connecting lines between nodes in the co-occurrence network reflect the link frequency of the keywords [149]; that is, the higher the link frequency between two keywords is, the thicker the connecting line is. This provides an indication of factors that were more closely related in the selection of strategy in a relative sense.

As shown in Figure 3, the co-occurrence network for the decommissioning strategy largely consists of four clusters. The index keywords in the surveyed articles are classified into blue (Cluster 1), red (Cluster 2), green (Cluster 3), and yellow parts (Cluster 4).

Cluster 1 is a cluster that is connected with six items: 'DD', 'health and safety', 'environmental impact', 'reactor and site characteristics', 'suitable technologies and techniques', and ‘technologies and techniques’. This part is composed of two factors, ‘health and safety’ and ‘environmental impact’, which are closely located in ‘DD’, which is the most frequent keyword and is linked with ‘reactor and site characteristics’, ‘suitable technologies and techniques’, and ‘technologies and techniques’; that is, articles that adopted the DD strategy mentioned health, safety and environmental impact (F4), reactor and site characteristics (F8), and suitable technologies and techniques (F7) frequently. Figure 4a shows detailed results of the keyword analysis in relation to the DD strategy.



(a) Deferred dismantling (b) Immediate dismantling



(c) Entombment

Figure 4. Results of the co-occurrence network analysis by strategy: (**a**) Keyword analysis of the DD strategy; (**b**) Keyword analysis of the ID strategy; (**c**) Keyword analysis of the ET strategy.

These results imply that the most important factor to consider when adopting a deferred dismantling strategy is to minimize the impact on the health and safety of workers and the environment. Subfactors related to these general factors show that reactor and NPP site characteristics should be strongly considered, and advanced reactor dismantling technology should be secured. In particular, when establishing a decommissioning strategy, potential accidents by workers should be reviewed, and the exposure doses of workers and residents should be managed and minimized. In addition, in order to prevent radiation exposure accidents, management procedures for workers should be prepared for each stage of dismantling.

Cluster 2 is a cluster that is connected with seven items: ‘ID’, ‘entombment’, ‘commercial issue’, ‘financial resources/cost of implementing a strategy’, ‘human resources’, ‘knowledge management’, and ‘knowledge management and human resources’. Both ID and entombment belong to this part of the decommissioning strategies. Out of the eight factors, it is closely related to financial resources/cost of implementing a strategy (F2) and knowledge management and human resources (F5). In particular, among the subfactors, the ‘commercial issue’ was mentioned often in research on the ID strategy and the entombment strategy, although its co-occurrence frequency was not that high. Figure 4b,c show the detailed analysis results for the ID and entombment strategies.

These results confirm that, for the immediate dismantling and entombment strategies, the financial resources for implementing these strategies are prioritized because the radioactive-material-contaminated structures, operating systems and devices, and sites must be demolished or removed as soon as possible after the permanent shutdown of the NPP. By analyzing the subfactors linked to these factors in the co-occurrence network, it was confirmed that elements of systematic decommissioning project management technologies, including their cost, schedule, and contaminated waste management, must be secured in order to secure economic feasibility. Therefore, when adopting the immediate dismantling and entombment strategy, more attention should be paid to not only the safety of workers but also to the evaluation of dismantling costs and the establishment of schedules.

Cluster 3 is a cluster that is connected to six items: ‘policies and regulatory framework’, ‘social impacts and stakeholder involvement’, ‘policy’, ‘regulatory framework’, ‘social impacts’, and ‘stakeholder involvement’. In addition, Cluster 4 refers to a cluster that is connected to three items: ‘spent fuel and waste management system’, ‘spent fuel’, and ‘waste management system’. The factors included in Clusters 3 and 4 are all connected to the three decommissioning strategies in a balanced manner, as shown in Figure 4; that is, of the eight general factors, policies and regulatory framework (F1), the spent fuel and waste management system (F3), and social impacts and stakeholder involvement (F6) were considered when determining a decommissioning strategy.s

As such, the network of the strategies visually displays the connection structures between index keywords and can be used in research to set a sustainable nuclear-decommissioning strategy in the future.

5.3. Discussion

As of 31 December 2020, France had the highest share of nuclear electricity generation at 71%, and 17 nations accounted for more than 20% of the share of nuclear electricity generation worldwide. Currently, 442 power reactors are running in 34 nations around the world, and 158 reactors are going through the decommissioning process or have already been decommissioned in 19 nations [2]. According to the global ‘Nuclear Decommissioning Market’ analysis report, it is predicted that 183 and 127 nuclear reactors will be decommissioned in the 2020s and 2030s, respectively [150]. The withdrawal of nuclear power has been actively sought in many nations in the European Union through the use of various types of renewable energy. Since the Fukushima Daiichi incident, countries such as Germany, France, and South Korea have taken drastic measures to phase out their nuclear power programs [150].

When establishing a decommissioning strategy for nuclear facilities, a process that is on the verge of expansion, radiological conditions, spent fuel and radioactive waste management and economics, and the development of suitable technology should be taken into consideration [130]. In this study, an SLR was conducted with a focus on three strategies, DD, ID, and ET, and eight general factors which should be considered when determining a strategy. These factors were selected using various study articles along with the IAEA publications. During the process of performing the quantitative and qualitative analyses, several noteworthy findings were verified, as follows:

First, the frequencies of selections of DD, ID, and ET as decommissioning strategies by the nations that are undergoing nuclear reactor decommissioning processes or where reactors have been decommissioned around the world (as presented in Table 3) are summarized in Table 5. As presented in Table 5, 5 out of the 17 nations account for 65 reactors, which is 90.3% of the total number that have undergone DD, and the UK, USA, and Japan account for the majority of these with 56 units. Out of the other 12 nations, 7 nations have adopted DD only for one reactor. ID has mostly been adopted in France, Germany, and the USA, while Belgium, Italy, South Korea, and Lithuania have only adopted ID. One of the reasons for nations to adopt ID is to allow the reuse of the sites, but public opinion also seems to play an important role in policy decision-making.

Table 5. Decommissioning strategies used by country (Source: research analysis results).

Country	DD	ID	ET	Total	Remarks
Belgium	-	1	-	1	Only DD, ID, and ET are summarized.
Bulgaria	4	-	-	4	
Canada	5	-	-	5	
France	-	10	-	10	
Germany	1	22	-	23	
Italy	-	3	-	3	
Japan	11	3	-	14	
Kazakhstan	1	-	-	1	
South Korea	-	2	-	2	
Lithuania	-	2	-	2	
The Netherlands	1	-	-	1	
Slovakia	1	2	-	3	
Spain	1	2	-	3	
Sweden	1	2	-	3	
Switzerland	1	1	-	2	
UK	25	1	-	26	
USA	20	9	3	32	
Total	72	60	3	135	

Second, Table 5 verifies that DD, ID, and ISD have been adopted unequally in all nations, except for the USA. This is because policy or political decision-making (F1) has played the most important role in choosing a strategy out of the eight general factors, as shown in Table 4. However, only 15 articles (12.6%) are mentioned, as presented in Table 4, from a research viewpoint. The reason for this is that F2, F3, F4, and F7 are easier to discuss academically than policy or political decision-making in terms of the researcher's standpoint. Furthermore, knowledge management (F5) has had a significant impact on the determination of the decommissioning strategy, but only five articles (4.2%) discussed the subject academically, which was the smallest number. This implies that more studies on F1 and F5 should be conducted in the future.

Third, the UK, the USA, and Japan, which own key player companies [150] in the global nuclear-decommissioning market, were found to have published relatively few articles, as shown in Table 1, compared with their numbers of owned NPPs and decommissioning records. This is because these countries have high levels of decommissioning technology and records already, so they are reluctant to publish academic papers in terms of a commercial viewpoint and the management of intellectual property rights. Nonetheless, the experience and knowledge of those nations should be more actively shared to promote the use of safe, economical, eco-friendly, and sustainable decommissioning strategies for NPPs while maintaining the health and prosperity of mankind. This is because all nuclear issues are not a problem of just one nation; they are global issues that should be of common concern to all nations.

6. Conclusions

The sustainable decommissioning of NPPs refers to the restoration of various types of NPP facilities whose service time has been terminated, and the surrounding environment is returned to its pre-NPP state to promote the safety, health, and prosperity of the current and future generations. The main sustainable NPP decommissioning strategies are DD, ID, and ET, and eight general factors are considered to guide the decommissioning policy. In this study, an SLR on decommissioning strategies involving eight general factors was conducted, and the following results were obtained.

First, the descriptive analysis results verified that nations with vast experience and knowledge of NPP decommissioning, such as the USA, the UK, Germany, and Japan, have not published corresponding research articles. Instead, nations, such as South Korea and Russia, that have just started NPP decommissioning and do not have major companies that are key players in the global nuclear-decommissioning market have published many research articles related to NPP decommissioning strategies, as presented in Table 1.

Second, this study verified that the number of articles on the NPP decommissioning strategy has rapidly increased since 1992 when the design life of many NPPs began globally. As shown in Figure 2, 105 (88.2%) out of 119 articles were published between 2001 and 2021. This trend will continue as the number of reactors to be decommissioned increases. As of 2020, globally, 158 reactors are undergoing the decommissioning process or have already been decommissioned [2], and an additional 310 reactors will be decommissioned by the 2030s [150].

Third, DD was mentioned in 117 articles (98.3%), while ID and ET were mentioned nearly the same number of times, in 61 (51.3%) and 60 (50.4%) articles, around half that of DD, as presented in Table 2. However, actual strategies applied to nuclear facility decommissioning showed that DD had been adopted for 72 units (45.6%), ID for 60 units (38.0%), and ET for three units (1.9%), as shown in Table 3. Despite the fact that ET has not been adopted in nations other than the USA, researchers have discussed ET as much as ID in their papers. This verifies there is a difference between the researchers' interests and the adopted strategies.

Fourth, the general factors that determined the decommissioning strategy were studied, and the results show that the health, safety, and environmental impact factor was the most commonly mentioned with 44 articles (37.0%), while the spent fuel and waste management system factor was mentioned in 36 articles (30.3%), as shown in Table 4. This result shows that researchers prioritize reducing occupational exposure, the blockage of radiation leakage, and the improvement of safety during decommissioning, while there should be more research on the safe handling of spent fuel and waste in the future.

Fifth, the co-occurrence network analysis result shows that DD strategy-related articles were intensively connected to the following factors, in order: 'health, safety, and environmental impact', 'reactor and site characteristics', and 'suitable technologies and techniques'. This means that the DD strategy should prioritize the health and safety of workers and strive to minimize the impact on the environment. In addition, ID and ET strategy-related articles were highly connected to 'financial resources/cost of implementing a strategy' and 'knowledge management and human resources'. This means that the ID and ET strategies should prioritize the cost and financial resources of implementing the strategy, as it is necessary to safely dismantle nuclear facilities as soon as possible after a permanent shutdown. Factors such as 'policies and regulatory framework', 'spent fuel and waste management system', and 'social impacts and stakeholder involvement' were not mentioned often but were found to be connected to all three decommissioning strategies.

This study found that many researchers were most interested in DD and discussed ID and ET at similar interest levels, but in the actual decommissioning industry, DD and ID are adopted equally, whereas ET has not been adopted, except for in the USA. Furthermore, in most nations that have adopted ID, political or policy decision-making seems to play an important role. Moreover, this study verified that major nations with decommissioning records and major companies do not actively share their experience or knowledge.

Based on the facts confirmed through this study, the authors suggest the following research directions for sustainable NPP decommissioning. First, research should be focused on DD and ID rather than on ET. Second, a study should be conducted to identify the correlations and influences between the decommissioning strategy and eight general factors. Third, it is necessary to study the techniques used for estimating the expected safety, cost, time, and environmental impact when selecting a strategy. Fourth, in order to establish the management of knowledge regarding safety, cost, time, and environmental impact, a technique should be developed to ensure that the requirements defined in the strategy and the detailed execution procedure established at the time of NPP decommissioning are met in a step-by-step manner. Fifth, it is necessary to develop a project management technique that is systematically applied from the initial stage to the completion of the NPP decommissioning process to ensure that there is a high level of safety and economic feasibility. Finally, it is necessary to establish a research hub where researchers from all over the world can share technology and knowledge related to sustainable NPP decommissioning.

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Abbreviations

NPP	Nuclear Power Plant
UCLA	University of California, Los Angeles
ID	Immediate Dismantling
DD	Deferred Dismantling
ET	Entombment
SE	Safe Enclosure
PD	Partial Dismantling
ISD	In Situ Disposal
IAEA	International Atomic Energy Agency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
WoS	Web of Sciences
SCIE	Science Citation Index Expanded
ISI	Institute for Scientific Information

References

1. Nuclear Energy Institute (NEI). The Advantages of Nuclear Energy. Available online: https://www.nei.org/advantages (accessed on 22 August 2021).
2. International Atomic Energy Agency (IAEA). Nuclear Power Reactors in the World, 2021 Edition. IAEA. 2021. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-2-41_web.pdf (accessed on 22 August 2021).
3. International Atomic Energy Agency (IAEA). The international nuclear and radiological event scale (INES). Available online: https://www.iaea.org/sites/default/files/ines.pdf (accessed on 22 August 2021).
4. Operational Performance Information System for Nuclear Power Plant (OPIS). Representative examples of INES classification criteria. Available online: https://opis.kins.re.kr/opis?act=KROCA2100R (accessed on 1 September 2021).
5. Hindmarsh, R.; Priestley, R. *The Fukushima Effect: A New Geopolitical Terrain*, 1st ed.; Routledge Studies in Science, Technology and Society; Routledge: New York, NY, USA, 2015. [CrossRef]
6. Nuclear Energy Institute (NEI). Decommissioning Nuclear Power Plants, Fact Sheet. NEI, 2016. Available online: https://www.nei.org/resources/fact-sheets/decommissioning-nuclear-power-plants (accessed on 22 August 2021).
7. Suh, Y.A.; Hornibrook, C.; Yim, M.S. Decisions on nuclear decommissioning strategies: Historical review. *Prog. Nucl. Energy* **2018**, *106*, 34–43. [CrossRef]
8. International Atomic Energy Agency (IAEA). Selection of Decommissioning Strategies: Issues and Factors. IAEA-TECDOC-1478, IAEA. 2005. Available online: https://www.iaea.org/publications/7393/selection-of-decommissioning-strategies-issues-and-factors (accessed on 2 September 2021).
9. International Atomic Energy Agency (IAEA). Policies and Strategies for the Decommissioning of Nuclear and Radiological Facilities. IAEA Nuclear Energy Series No. NW-G-2.1. 2011. Available online: https://www.iaea.org/publications/8659/policies-and-strategies-for-the-decommissioning-of-nuclear-and-radiological-facilities (accessed on 2 September 2021).
10. Laraia, M. *Nuclear Decommissioning. Planning, Execution and International Experience*; Woodhead Publishing: Sawston, UK, 2012.

11. Bayliss, C.; Langley, K. *Nuclear Decommissioning, Waste Management, and Environmental Site Remediation*; Elsevier: Amsterdam, The Netherlands, 2003.
12. Szőke, I.; Louka, M.N.; Bryntesen, T.R.; Edvardsen, S.T.; Bratteli, J. Comprehensive support for nuclear decommissioning based on 3D simulation and advanced user interface technologies. *J. Nucl. Sci. Technol.* **2015**, *52*, 371–387. [CrossRef]
13. Volk, R.; Hübner, F.; Hünlich, T.; Schultmann, F. The future of nuclear decommissioning–A worldwide market potential study. *Energy Policy* **2019**, *124*, 226–261. [CrossRef]
14. Asahara, A.; Kawasaki, D.; Yanagihara, S. Study on strategy construction for dismantling and radioactive waste management at Fukushima Daiichi Nuclear Power Station. *Nucl. Eng. Des.* **2021**, *374*, 111066. [CrossRef]
15. Lough, W.T.; White, K.P., Jr. A critical review of nuclear power plant decommissioning planning studies. *Energy Policy* **1990**, *18*, 471–479. [CrossRef]
16. Bond, A.; Bussell, M.; O'Sullivan, P.; Palerm, J. Environmental impact assessment and the decommissioning of nuclear power plants—a review and suggestion for a best practicable approach. *Environ. Impact Assess. Rev.* **2003**, *23*, 197–217. [CrossRef]
17. Devgun, J.S. A review of decommissioning considerations for new reactors. In Proceedings of the WM2008 Conference, Phoenix, AZ, USA, 24–28 February 2008.
18. Crompton, A.J.; Gamage, K.A.; Jenkins, A.; Taylor, C.J. Alpha particle detection using alpha-induced air radioluminescence: A review and future prospects for preliminary radiological characterisation for nuclear facilities decommissioning. *Sensors* **2018**, *18*, 1015. [CrossRef]
19. Croudace, I.W.; Russell, B.C.; Warwick, P.W. Plasma source mass spectrometry for radioactive waste characterisation in support of nuclear decommissioning: A review. *J. Anal. At. Spectrom.* **2017**, *32*, 494–526. [CrossRef]
20. Remeikis, V.; Grineviciute, J.; Duškesas, G.; Juodis, L.; Plukienė, R.; Plukis, A. Review of modeling experience during operation and decommissioning of RBMK-1500 reactors. I. Safety improvement studies during operation. *Nucl. Eng. Des.* **2021**, *380*, 110952. [CrossRef]
21. Bogue, R. Robots in the nuclear industry: A review of technologies and applications. *Ind. Robot. Int. J.* **2001**, *38*, 113–118. [CrossRef]
22. Kim, S. Special Issue Technology and Management for Sustainable Buildings and Infrastructures, Special Issue Information. Available online: https://www.mdpi.com/journal/sustainability/special_issues/Technology_sensors (accessed on 6 September 2021).
23. Randers, J.; Behrens, W.W.; Pestel, E. The Limits to Growth: A Report to The Club of Rome (1972). 2007. Available online: https://web.ics.purdue.edu/~{}wggray/Teaching/His300/Illustrations/Limits-to-Growth.pdf (accessed on 6 September 2021).
24. U.S. Environmental Protection Agency (US EPA). What Is Sustainability? Available online: https://www.epa.gov/sustainability/learn-about-sustainability#what (accessed on 6 September 2021).
25. University of California, Los Angeles (UCLA). What is Sustainability? Available online: https://www.sustain.ucla.edu/what-is-sustainability/ (accessed on 6 September 2021).
26. Oxford. Sustainability, UK Dictionary. Available online: https://www.lexico.com/definition/sustainability (accessed on 8 September 2021).
27. Gillin, K. The benefits of sustainable decommissioning approach, Lloyd's Register, 12 March 2019. Available online: https://www.lr.org/en/insights/sustainability/the-benefits-of-a-sustainable-decommissioning-approach/ (accessed on 1 November 2021).
28. Wikipedia. Strategy. Available online: https://en.wikipedia.org/wiki/Strategy (accessed on 26 December 2021).
29. Freedman, L. *Strategy*; Oxford University Press: Oxford, UK, 2013; ISBN 978-0-19-932515-3.
30. Mintzberg, H.; Quinn, J.B. *The Strategy Process: Concepts, Contexts, Cases*; Prentice Hall: Hoboken, NJ, USA, 1996; ISBN 978-0-132-340304.
31. World Nuclear News. REVIEW: Planning Ahead for Decommissioning. Available online: https://www.world-nuclear-news.org/Articles/REVIEW-Planning-ahead-for-decommissioning (accessed on 1 November 2021).
32. Organisation for Economic Co-operation and Development (OECD). *Selecting Strategies for the Decommissioning of Nuclear Facilities, A Status Report*; Nuclear Energy Agency (NEA): Paris, France; OECD: Paris, France, 2006; ISBN 92-64-02305-4.
33. European Commission (EC). *Analysis of the Factors Influencing the Selection of Strategies for Decommissioning of Nuclear Installations*; Final reports; EC: Brussels, Belgium, 2005.
34. Thierfeldt, S. Safe enclosure and entombment strategies in nuclear decommissioning projects. In *Nuclear Decommissioning*; Woodhead Publishing: Sawston, UK, 2012; pp. 245–292. [CrossRef]
35. Laraia, M. Reuse and redevelopment of decommissioned nuclear sites: Strategies and lessons learned. In *Nuclear Decommissioning*; Woodhead Publishing: Sawston, UK, 2012; pp. 475–510. [CrossRef]
36. Zohuri, B. Nuclear fuel cycle and decommissioning. In *Nuclear Reactor Technology Development and Utilization*; Woodhead Publishing: Sawston, UK, 2020; pp. 61–120. [CrossRef]
37. Lainetti, P.D.O.; de Freitas, A.A.; Mindrisz, A.C.; Camilo, R.L. Decommissioning of Nuclear Fuel Cycle Facilities in the IPEN-CNEN/SP. 2007. Available online: https://www.ipen.br/biblioteca/2007/eventos/13964.pdf (accessed on 9 November 2021).
38. Leclair, A.N.; Lemire, D.S. Information management for nuclear decommissioning projects. In *Nuclear Decommissioning*; Woodhead Publishing: Sawston, UK, 2012; pp. 777–798. [CrossRef]
39. Borrmann, F. Knowledge management toward, during, and after decommissioning. In *Advances and Innovations in Nuclear Decommissioning*; Woodhead Publishing: Sawston, UK, 2017; pp. 73–90. [CrossRef]

40. Monteiro, D.B.; Moreira, J.M.L.; Maiorino, J.R. A method for decommissioning strategy proposal and a cost estimation considering a multiple reactor site with interdependent plants. *Prog. Nucl. Energy* **2020**, *127*, 103440. [CrossRef]
41. Monteiro, D.B.; Moreira, J.M.L.; Maiorino, J.R. A new management tool and mathematical model for decommissioning cost estimation of multiple reactors site. *Prog. Nucl. Energy* **2019**, *114*, 61–83. [CrossRef]
42. Hoang, P.T.; Choi, Y.S.; Rhee, I.; Kang, G.; Choi, H.R. A new torque minimization method for heavy-duty redundant manipulators used in nuclear decommissioning tasks. *Intell. Serv. Robot.* **2021**, *14*, 459–469. [CrossRef]
43. Jeong, K.; Choi, M.; Kim, A.; Lee, J.; Lee, B. A systematic approach to the effective strategy and plan of stakeholders for safety improvement during decommissioning of nuclear facilities. *Ann. Nucl. Energy* **2021**, *158*, 108307. [CrossRef]
44. Jeong, K.; Choi, B.; Moon, J.; Hyun, D.; Lee, J.; Kim, I.; Seo, J. An evaluation of the dismantling technologies for decommissioning of nuclear power plants. *Ann. Nucl. Energy* **2014**, *69*, 62–64. [CrossRef]
45. Greenwood, D.F.; Westfahl, R.K.; Rymsha, J.W. Analysis of decommissioning costs for nuclear power reactors. *Nucl. Technol.* **1983**, *62*, 190–206. [CrossRef]
46. Bogatov, S.A.; Vysotskii, V.L.; Sarkisov, A.A.; Pologikh, B.G.; Sivintsev, Y.V.; Nikitin, V.S. Analysis of the radioactive contamination of the environment due to decommissioned objects of the nuclear-powered fleet in northwestern Russia. *At. Energy* **2006**, *101*, 485–493. [CrossRef]
47. Kim, S.I.; Lee, H.Y.; Song, J.S. A study on characteristics and internal exposure evaluation of radioactive aerosols during pipe cutting in decommissioning of nuclear power plant. *Nucl. Eng. Technol.* **2018**, *50*, 1088–1098. [CrossRef]
48. Chae, N.; Lee, M.H.; Choi, S.; Park, B.G.; Song, J.S. Aerodynamic diameter and radioactivity distributions of radioactive aerosols from activated metals cutting for nuclear power plant decommissioning. *J. Hazard. Mater.* **2019**, *369*, 727–745. [CrossRef]
49. Seo, H.W.; Oh, J.Y.; Yu, J.H.; Jo, K.H. Calculation approach to building DCGLs of waste treatment facility for Kori unit 1 decommissioning and comparative analysis of the results. *Ann. Nucl. Energy* **2021**, *153*, 108009. [CrossRef]
50. Seo, H.W.; Sohn, W. Calculation of preliminary site-specific DCGLs for nuclear power plant decommissioning using hybrid scenarios. *Nucl. Eng. Technol.* **2019**, *51*, 1098–1108. [CrossRef]
51. Lee, C.; Kim, H.R.; Lee, S.J. Comparison of occupational exposure according to dismantling strategy of Kori nuclear power plant unit# 1 bio-shield. *Ann. Nucl. Energy* **2021**, *157*, 108227. [CrossRef]
52. Songa, M.; Kim, C.L.; Kessel, D.S. Consideration of spent fuel pool island as an interim management option of spent nuclear fuel for Kori unit 3 & 4 during decommissioning of Kori site. *Energy Strategy Rev.* **2018**, *21*, 163–171. [CrossRef]
53. Han, S.; Hong, S.; Nam, S.; Kim, W.S.; Um, W. Decontamination of concrete waste from nuclear power plant decommissioning in South Korea. *Ann. Nucl. Energy* **2020**, *149*, 107795. [CrossRef]
54. Jeong, K.S.; Choi, B.S.; Moon, J.K.; Hyun, D.J.; Lee, J.H.; Kim, G.H.; Lee, J.J. Evaluation of alternative removal methods for decommissioning of heavy components in nuclear power plants. *Ann. Nucl. Energy* **2014**, *63*, 506–508. [CrossRef]
55. Chen, Y.S.; Huang, L.Y. Evaluation of the reactor building environmental conditions under a LOCA for the decommissioning Chinshan plant. *Ann. Nucl. Energy* **2021**, *156*, 108205. [CrossRef]
56. Choi, W.J.; Roh, M.S.; Kim, C.L. Innovative Nuclear Power Plant Building Arrangement in Consideration of Decommissioning. *Nucl. Eng. Technol.* **2017**, *49*, 525–533. [CrossRef]
57. Pyo, J.Y.; Um, W.; Heo, J. Magnesium potassium phosphate cements to immobilize radioactive concrete wastes generated by decommissioning of nuclear power plants. *Nucl. Eng. Technol.* **2021**, *53*, 2261–2267. [CrossRef]
58. Lee, M.H.; Yang, W.; Chae, N.; Choi, S. Performance assessment of HEPA filter against radioactive aerosols from metal cutting during nuclear decommissioning. *Nucl. Eng. Technol.* **2020**, *52*, 1043–1050. [CrossRef]
59. Lee, S.H.; Seo, H.W.; Kim, C.L. Preparation of radiological environmental impact assessment for the decommissioning of nuclear power plant in Korea. *J. Nucl. Fuel Cycle Waste Technol. (JNFCWT)* **2018**, *16*, 107–122. [CrossRef]
60. Seo, H.W.; Lee, D.H.; Kessel, D.S.; Kim, C.L. Proposal for the management strategy of metallic waste from the decommissioning of kori unit 1 by using melting and segmentation technology. *Ann. Nucl. Energy* **2017**, *110*, 633–647. [CrossRef]
61. Seo, H.W.; Sohn, W.; Jo, K.H. Proposal for the spent nuclear fuel management plan from the decommissioning of Kori site NPPs. *Ann. Nucl. Energy* **2018**, *120*, 749–762. [CrossRef]
62. Jeong, K.S.; Choi, B.S.; Moon, J.K.; Hyun, D.J.; Kim, G.H.; Kim, T.H.; Lee, J.J. Radiological assessment for decommissioning of major component in nuclear power plants. *Ann. Nucl. Energy* **2014**, *63*, 571–574. [CrossRef]
63. Choi, Y.; Ko, J.; Lee, D.; Kim, H.; Park, K.; Sohn, H. Safety Assessment for the self-disposal plan of clearance radioactive waste after nuclear power plant decommissioning. *J. Energy Eng.* **2020**, *29*, 63–74. [CrossRef]
64. Kim, H.; Lee, D.; Lee, C.W.; Kim, H.R.; Lee, S.J. Safety Assessment Framework for Nuclear Power Plant Decommissioning Workers. *IEEE Access* **2019**, *7*, 76305–76316. [CrossRef]
65. Kim, J.H.; Hornibrook, C.; Yim, M.S. The impact of below detection limit samples in residual risk assessments for decommissioning nuclear power plant sites. *J. Environ. Radioact.* **2020**, *222*, 106340. [CrossRef]
66. Kim, D.; Croudace, I.W.; Warwick, P.E. The requirement for proper storage of nuclear and related decommissioning samples to safeguard accuracy of tritium data. *J. Hazard. Mater.* **2012**, *213*, 292–298. [CrossRef]
67. Moon, J.; Kim, S.; Choi, W.; Choi, B.; Chung, D.; Seo, B. The status and prospect of decommissioning technology development at KAERI. *J. Nucl. Fuel Cycle Waste Technol. (JNFCWT)* **2019**, *17*, 139–165. [CrossRef]

68. Shin, J.S.; Oh, S.Y.; Park, S.; Park, H.; Kim, T.S.; Lee, L.; Lee, J. Underwater laser cutting of stainless steel up to 100 mm thick for dismantling application in nuclear power plants. *Ann. Nucl. Energy* **2020**, *147*, 107655. [CrossRef]
69. Tsypin, S.G.; Sharafutdinov, R.B. Characteristic features of the decommissioning of fuel-cycle nonreactor nuclear systems and radiation sources. *At. Energy* **2000**, *88*, 236–238. [CrossRef]
70. Bylkin, B.; Pereguda, V.; Shaposhnikov, V.; Tikhonovskii, V. Composition and structure of simulation models for evaluating decommissioning costs for nuclear power plant units. *At. Energy* **2011**, *110*, 77. [CrossRef]
71. Bylkin, B.K.; Shaposhnikov, V.A.; Sadovoi, Y.K.; Tikhonovskii, V.L. Database for decommissioning power-generating units at the Leningrad nuclear power plant. *At. Energy* **2003**, *95*, 591–596. [CrossRef]
72. Simanovskii, Y.M.; Safutin, V.D.; Tokarenko, A.I.; Khmel'shchikov, V.V.; Chepurnoi, Y.A. Decommissioning and Disassembly of a Research Reactor at the Noril'sk Integrated Mining–Metallurgical Plant. *At. Energy* **2003**, *95*, 521–527. [CrossRef]
73. Kulikov, I.D.; Safutin, V.D.; Simanovskii, V.M.; Abramov, M.I.; Bylkin, B.K.; Zverkov, Y.A.; Nikolaev, A.G. Decommissioning industrial uranium-graphite reactors. *At. Energy* **1999**, *87*, 569–576. [CrossRef]
74. Engovatov, I.A.; Mashkovich, V.P.; Orlov, Y.V.; Pologikh, B.G.; Khlopkin, N.S.; Tsypin, S.G. Decommissioning of civil and military reactors. *At. Energy* **1998**, *85*, 706–709. [CrossRef]
75. Ryazantsev, E.P.; Kolyadin, V.I.; Egorenkov, P.M.; Smirnov, A.M.; Kukharkin, N.E.; Bylkin, B.K.; Zverkov, Y.A. Decommissioning of nuclear and radiation-hazardous objects of the russian science center "Kurchatov Institute". *At. Energy* **1999**, *87*, 631–639. [CrossRef]
76. Poluektov, P.P.; Sukhanov, L.P.; Chernikov, M.A.; Chizhov, A.A.; Felitsyn, M.A. Decontamination and decommissioning of radioactively contaminated rooms and equipment at the Bochvar All-Russia Research Institute of Standardization in Machine Engineering. *At. Energy* **2008**, *105*, 60–64. [CrossRef]
77. Berela, A.I.; Sorokin, V.N.; Shpitser, V.Y.; Étingen, A.A.; Bylkin, B.K.; Makhov, V.A.; Morozov, V.G. Developing technology for decommissioning nuclear power stations. *At. Energy* **1997**, *83*, 890–893. [CrossRef]
78. Bylkin, B.K.; Berela, A.I.; Kopytov, I.I. Development in a nuclear power station project of matters concerning the dismantling of equipment at the stage of power unit decommissioning. *Therm. Eng.* **2006**, *53*, 743–748. [CrossRef]
79. Bykov, A.A.; Bylkin, B.K.; Gorlinskii, Y.E.; Gudimov, R.S.; Drozdov, A.A.; Zverkov, Y.A.; Samarin, E.N. Experience in international collaboration in the development of preliminary plans for decommissioning nuclear research facilities at the Russian science center Kurchatov institute. *At. Energy* **2009**, *107*, 225. [CrossRef]
80. Stepanov, A.I.; Doil'nitsyn, V.A. Foam-and Film-Forming Compositions and Technical Means for Accident-Remediation and Disassembly Work on Nuclear Power Facilities. *At. Energy* **2008**, *105*, 75–77. [CrossRef]
81. Bylkin, B.K.; Gorelov, K.A.; Engovatov, I.A.; Zaitsev, A.N.; Zimin, V.K.; Musorin, A.I.; Nozdrin, G.N. Improvement of regulatory documents on decommissioning power-generating units of nuclear power plants. *At. Energy* **2009**, *107*, 369–373. [CrossRef]
82. Bugaenko, S.E.; Arzhaev, A.I.; Evropin, S.V.; Savchenko, V.A. Management of the service life of a nuclear Power Plant. *At. Energy* **2002**, *92*, 279–286. [CrossRef]
83. Tikhonovskii, V.L.; Kononov, V.V.; Chuiko, D.V.; Bylkin, B.K.; Shaposhnikov, V.A. Methods for representing and organizing information for a database on decommissioning power-generating units in nuclear power plants. *At. Energy* **2007**, *103*, 990–994. [CrossRef]
84. Nazarov, V.; Frontasyeva, M.; Lavdanskij, P.; Stephanov, N. NAA for optimization of radiation shielding of nuclear power plants. *J. Radioanal. Nucl. Chem.* **1994**, *180*, 83–95. [CrossRef]
85. Fedosov, A.M. Optimal fuel utilization during decommissioning of nuclear power plants with RBMK reactors. *At. Energy* **2007**, *102*, 353–360. [CrossRef]
86. Frolov, V.V.; Kryuchkov, A.V.; Kuznetsov, Y.N.; Moskin, V.A.; Pankrat'ev, Y.V.; Romenkov, A.A. Possibility of burning irradiated graphite from decommissioned nuclear power-generating units. *At. Energy* **2004**, *97*, 781–784. [CrossRef]
87. Volkov, V.G.; Zverkov, Y.A.; Kolyadin, V.I.; Lemus, A.V.; Muzrukova, V.D.; Pavlenko, V.I.; Shisha, A.D. Preparations for decommissioning the MR research reactor at the Russian Science Center Kurchatov institute. *At. Energy* **2008**, *104*, 335–341. [CrossRef]
88. Bylkin, B.K.; Berela, A.I. Problem-oriented system for designing a technology for disassembling equipment for decommissioning the power-generating units of a nuclear power plant. *At. Energy* **2000**, *89*, 701–708. [CrossRef]
89. Shadrin, A.P.; Kuz'min, A.N. Radioactive waste utilization and decommissioning of low-power nuclear power stations under arctic conditions. *At. Energy* **1997**, *83*, 573–575. [CrossRef]
90. Bylkin, B.K.; Davydova, G.B.; Zhurbenko, E.A. Radwastes from disassembly of nuclear power plant reactor units. *At. Energy* **2011**, *110*, 203. [CrossRef]
91. Hoeppener-Kramar, U.; Pimpl, M.; Willmann, F. Application of procedures for low level radionuclide analysis in environmental monitoring for the purpose of clearance measurements of materials from decommissioning of nuclear facilities. *J. Radioanal. Nucl. Chem.* **1997**, *226*, 99–103. [CrossRef]
92. Volkmann, B.; Löschhorn, U. Aspects on decommissioning of the Greifswald nuclear power plant. *Nucl. Eng. Des.* **1995**, *159*, 117–121. [CrossRef]
93. Delakowitz, B.; Meinrath, G. Decommissioning of a nuclear power plant: Determination of site-specific sorption coefficients for Co-60 and Cs-137. *Isot. Environ. Health Stud.* **1998**, *34*, 371–380. [CrossRef]

94. Brendebach, B. Decommissioning of nuclear facilities: Germany's experience. *IAEA Bull.* **2016**, *57*, 24–25.
95. Zapata-García, D.; Wershofen, H. Development of radiochemical analysis strategies for decommissioning activities. *Appl. Radiat. Isot.* **2017**, *126*, 204–207. [CrossRef]
96. Viehrig, H.W.; Altstadt, E.; Houska, M.; Valo, M. Fracture mechanics characterisation of the beltline welding seam of the decommissioned WWER-440 reactor pressure vessel of nuclear power plant Greifswald Unit 4. *Int. J. Press. Vessel. Pip.* **2012**, *89*, 129–136. [CrossRef]
97. Ehlert, A. Implementation of Knowledge Management in the Decommissioning of Nuclear Power Stations of E. ON Kernkraft GmbH. No. IAEA-CN–153. 2007. Available online: https://inis.iaea.org/search/search.aspx?orig_q=RN:38067982 (accessed on 9 November 2021).
98. Kirschnick, F.; Engelhardt, S. Knowledge Management for the Decommissioning of Nuclear Power Plants. No. IAEA-CN–123. 2004. Available online: https://inis.iaea.org/search/search.aspx?orig_q=RN:35088787 (accessed on 9 November 2021).
99. Seher, H.; Navarro, M.; Artmann, A.; Larue, J.; Roloff, R.; Weiß, D. Modelling contaminant transport in generic landfills for decommissioning waste from German nuclear power plants. *Prog. Nucl. Energy* **2016**, *89*, 46–56. [CrossRef]
100. Invernizzi, D.C.; Locatelli, G.; Grönqvist, M.; Brookes, N.J. Applying value management when it seems that there is no value to be managed: The case of nuclear decommissioning. *Int. J. Proj. Manag.* **2019**, *37*, 668–683. [CrossRef]
101. Braysher, E.; Russell, B.; Woods, S.; García-Miranda, M.; Ivanov, P.; Bouchard, B.; Read, D. Complete dissolution of solid matrices using automated borate fusion in support of nuclear decommissioning and production of reference materials. *J. Radioanal. Nucl. Chem.* **2019**, *321*, 183–196. [CrossRef]
102. Hicks, D.I.; Crittenden, B.D.; Warhurst, A.C. Design for decommissioning: Addressing the future closure of chemical sites in the design of new plant. *Process Saf. Environ. Prot.* **2000**, *78*, 465–479. [CrossRef]
103. Bond, A.; Palerm, J.; Haigh, P. Public participation in EIA of nuclear power plant decommissioning projects: A case study analysis. *Environ. Impact Assess. Rev.* **2004**, *24*, 617–641. [CrossRef]
104. Coffey, P.; Smith, N.; Lennox, B.; Kijne, G.; Bowen, B.; Davis-Johnston, A.; Martin, P.A. Robotic arm material characterisation using LIBS and Raman in a nuclear hot cell decommissioning environment. *J. Hazard. Mater.* **2021**, *412*, 125193. [CrossRef] [PubMed]
105. Di Buono, A.; Cockbain, N.; Green, P.R.; Lennox, B. The effects of Total Ionizing Dose irradiation on supercapacitors deployed in nuclear decommissioning environments. *J. Power Sources* **2020**, *479*, 228675. [CrossRef]
106. Gardner, L.J.; Walling, S.A.; Corkhill, C.L.; Hyatt, N.C. Thermal treatment of Cs-exchanged chabazite by hot isostatic pressing to support decommissioning of Fukushima Daiichi Nuclear Power Plant. *J. Hazard. Mater.* **2021**, *413*, 125250. [CrossRef]
107. Purkis, J.M.; Warwick, P.E.; Graham, J.; Hemming, S.D.; Cundy, A.B. Towards the application of electrokinetic remediation for nuclear site decommissioning. *J. Hazard. Mat.* **2021**, *413*, 125274. [CrossRef]
108. Sun, H.; Qu, J.; Wang, P.; Kang, J. Application of the Analytic Hierarchy Process in the Selection of Nuclear Power Plant Decommissioning Strategy. In Proceedings of the 24th International Conference on Nuclear Engineering, Charlotte, NC, USA, 26–30 June 2016; American Society of Mechanical Engineers: New York, NY, USA, 2016; Volume 50053, p. V005T15A004. [CrossRef]
109. Greco, A.; Yamamoto, D. Geographical political economy of nuclear power plant closures. *Geoforum* **2019**, *106*, 234–243. [CrossRef]
110. Rod McCullu. Nuclear Power Plant Decommissioning. *J. Encycl. Nucl. Energy* **2021**, 240–246. [CrossRef]
111. Schroeder, R.; Sevin, S.; Yarbrough, K. Reporting effects of SFAS 143 on nuclear decommissioning costs. *Int. Adv. Econ. Res.* **2005**, *11*, 449–458. [CrossRef]
112. Rempe, J.L. Safety, Regulation, and Decommissioning of Commercial Nuclear Power Reactors—Introduction. In *Encyclopedia of Nuclear Energy*; Elsevier: Amsterdam, The Netherlands, 2021. [CrossRef]
113. Uchida, S.; Karasawa, H.; Kino, C.; Pellegrini, M.; Naitoh, M.; Ohsaka, M. An approach toward evaluation of long-term fission product distributions in the Fukushima Daiichi nuclear power plant after the severe accident. *Nucl. Eng. Des.* **2021**, *380*, 111256. [CrossRef]
114. Kudo, S.; Sugihara, T. Basic concept of safety evaluation method for decommissioning of nuclear power plants by applying a graded approach. *Nucl. Eng. Des.* **2021**, *379*, 111212. [CrossRef]
115. Takashima, R.; Naito, Y.; Kimura, H.; Madarame, H. Decommissioning and equipment replacement of nuclear power plants under uncertainty. *J. Nucl. Sci. Technol.* **2007**, *44*, 1347–1355. [CrossRef]
116. Iguchi, Y.; Kanehira, Y.; Tachibana, M.; Johnsen, T. Development of decommissioning engineering support system (dexus of the fugen nuclear power station. *J. Nucl. Sci. Technol.* **2004**, *41*, 367–375. [CrossRef]
117. Iguchi, Y.; Yanagihara, S. Integration of knowledge management system for the decommissioning of nuclear facilities. *Mech. Eng. J.* **2016**, *3*, 15–00518. [CrossRef]
118. Yamaguchi, A.; Jang, S.; Hida, K.; Yamanaka, Y.; Narumiya, Y. Risk assessment strategy for decommissioning of Fukushima Daiichi nuclear power station. *Nucl. Eng. Technol.* **2017**, *49*, 442–449. [CrossRef]
119. Zhang, Z.; Song, Y.; Ma, S.; Guo, Y.; Li, C. A rapid coupling method for calculating the radiation field in decommissioning nuclear power plants. *Ann. Nucl. Energy* **2021**, *156*, 108179. [CrossRef]
120. Li, F.; Wang, J.; Li, H.; Hu, Q.; Dan, W.; Ge, L.; Cohen, D. Evaluation on nuclear emergency response strategies in the Asia-Pacific region. *Int. J. Crit. Infrastruct. Prot.* **2021**, *34*, 100447. [CrossRef]

121. Awodi, N.J.; Liu, Y.K.; Ayodeji, A.; Adibeli, J.O. Expert judgement-based risk factor identification and analysis for an effective nuclear decommissioning risk assessment modeling. *Prog. Nucl. Energy* **2021**, *136*, 103733. [CrossRef]
122. Adibeli, J.O.; Liu, Y.K.; Ayodeji, A.; Awodi, N.J. Path planning in nuclear facility decommissioning: Research status, challenges, and opportunities. *Nucl. Eng. Technol.* **2021**, *53*, 3505–3516. [CrossRef]
123. Yang, L.Q.; Liu, Y.K.; Peng, M.J.; Ayodeji, A.; Chen, Z.T.; Long, Z.Y. Radioactive gas diffusion simulation and inhaled effective dose evaluation during nuclear decommissioning. *Nucl. Eng. Technol.* **2021**, *54*, 293–300. [CrossRef]
124. Bednár, D.; Lištjak, M.; Slimák, A.; Nečas, V. Comparison of deterministic and stochastic methods for external gamma dose rate calculation in the decommissioning of nuclear power plants. *Ann. Nucl. Energy* **2019**, *134*, 67–76. [CrossRef]
125. Robredo, L.M.; Navarro, T.; Sierra, I. Indirect monitoring of internal exposure in the decommissioning of a nuclear power plant in Spain. *Appl. Radiat. Isot.* **2000**, *53*, 345–350. [CrossRef]
126. Sanchez-Cabeza, J.A.; Molero, J. Plutonium, americium and radiocaesium in the marine environment close to the Vandellós I nuclear power plant before decommissioning. *J. Environ. Radioact.* **2000**, *51*, 211–228. [CrossRef]
127. Herranz, M.; Boden, S.; Völgyesi, P.; Idoeta, R.; Broeckx, W.; González, J.R.; Legarda, F. Radiological characterisation in view of nuclear reactor decommissioning: On-site benchmarking exercise of a biological shield. *Prog. Nucl. Energy* **2021**, *137*, 103740. [CrossRef]
128. Diaz-Maurin, F.; Yu, J.; Ewing, R.C. Socio-technical multi-criteria evaluation of long-term spent nuclear fuel management strategies: A framework and method. *Sci. Total Environ.* **2021**, *777*, 146086. [CrossRef] [PubMed]
129. Aspe, F.; Idoeta, R.; Auge, G.; Herranz, M. Classification and categorization of the constrained environments in nuclear/radiological installations under decommissioning and dismantling processes. *Prog. Nucl. Energy* **2020**, *124*, 103347. [CrossRef]
130. Laraia, M. Decommissioning Strategies Worldwide: A Re-Visited Overview of Relevant Factors. In Proceedings of the ASME 2009 12th International Conference on Environmental Remediation and Radioactive Waste Management, Liverpool, UK, 11–15 October 2009; Volume 44083, pp. 263–273. [CrossRef]
131. Chen, Y.F.; Lin, Y.K.; Sheu, R.J.; Jiang, S.H. Evaluation of Radionuclides in Concrete Shielding for Nuclear Power Plant Decommissioning. *Nucl. Technol.* **2009**, *168*, 508–512. [CrossRef]
132. Slimák, A.; Nečas, V. Melting of contaminated metallic materials in the process of the decommissioning of nuclear power plants. *Prog. Nucl. Energy* **2016**, *92*, 29–39. [CrossRef]
133. Hrncir, T.; Strazovec, R.; Zachar, M. Potential for recycling of slightly radioactive metals arising from decommissioning within nuclear sector in Slovakia. *J. Environ. Radioact.* **2019**, *196*, 212–224. [CrossRef]
134. Liu, R.F.; Chen, C.K.; Yang, P.Y. Safety aspects of spent fuel management in nuclear power plants during transition to decommissioning. *Ann. Nucl. Energy* **2020**, *144*, 107469. [CrossRef]
135. Chen, Y.S. Thermal analysis for the integrated spent fuel pool of the Chinshan plant in the decommissioning process. *Ann. Nucl. Energy* **2018**, *119*, 163–174. [CrossRef]
136. Laraia, M. Worldwide current strategies, issues and trends on decommissioning of nuclear power plants: New emphasis on WWERs in the IAEA decommissioning programme. *Dokladi BYaD* **2001**, *6*, 66–78.
137. Rimkevičius, S.; Vaišnoras, M.; Babilas, E.; Ušpuras, E. HAZOP application for the nuclear power plants decommissioning projects. *Ann. Nucl. Energy* **2016**, *94*, 461–471. [CrossRef]
138. Remeikis, V.; Grineviciute, J.; Duškesas, G.; Juodis, L.; Plukienė, R.; Plukis, A. Review of modeling experience during operation and decommissioning of RBMK-1500 reactors. II. Radioactive waste management. *Nucl. Eng. Des.* **2021**, *380*, 111242. [CrossRef]
139. Starý, M.; Novotný, F.; Horák, M.; Stará, M. Sampling robot for primary circuit pipelines of decommissioned nuclear facilities. *Autom. Constr.* **2020**, *119*, 103303. [CrossRef]
140. Adámek, A.; Pražský, M.; Binka, J. Some problems with determination of alpha-active nuclides during decommissioning of nuclear power plant A-1. *J. Radioanal. Nucl. Chem.* **1988**, *121*, 395–401. [CrossRef]
141. Amft, M.; Leisvik, M.; Carroll, S. Applying and adapting the Swedish regulatory system for decommissioning to nuclear power reactors–The regulator's perspective. *J. Environ. Radioact.* **2019**, *196*, 181–186. [CrossRef]
142. Volmert, B.; Bykov, V.; Petrovic, D.; Kickhofel, J.; Amosova, N.; Kim, J.H.; Cho, C.W. Illustration of Nagra's AMAC approach to Kori-1 NPP decommissioning based on experience from its detailed application to Swiss NPPs. *Nucl. Eng. Technol.* **2021**, *53*, 1491–1510. [CrossRef]
143. Jarjies, A.; Abbas, M.; Fernandes, H.M.; Wong, M.; Coates, R. Prioritization methodology for the decommissioning of nuclear facilities: A study case on the Iraq former nuclear complex. *J. Environ. Radioact.* **2013**, *119*, 70–78. [CrossRef]
144. Testa, C.; Desideri, D.; Meli, M.A.; Roselli, C.; Queirazza, G.; Bazzarri, S. Radioanalytical procedures for the separation and determination of alpha, beta and X emitters in environmental samples of a nuclear power plant before decommissioning. *Sci. Total Environ.* **1993**, *130*, 403–417. [CrossRef]
145. Hou, X. Radiochemical analysis of radionuclides difficult to measure for waste characterization in decommissioning of nuclear facilities. *J. Radioanal. Nucl. Chem.* **2007**, *273*, 43–48. [CrossRef]
146. Hoti, F.; Perko, T.; Thijssen, P.; Renn, O. Who is willing to participate? Examining public participation intention concerning decommissioning of nuclear power plants in Belgium. *Energy Policy* **2021**, *157*, 112488. [CrossRef]
147. Statista. Number of Operable Nuclear Reactors Worldwide as of October 2021, by Country. Available online: https://www.statista.com/statistics/267158/number-of-nuclear-reactors-in-operation-by-country/ (accessed on 11 February 2022).

148. Lordan-Perret, R.; Sloan, R.D.; Rosner, R. Decommissioning the US nuclear fleet: Financial assurance, corporate structures, and bankruptcy. *Energy Policy* **2021**, *154*, 112280. [CrossRef]
149. Freilich, S.; Kreimer, A.; Meilijson, I.; Gophna, U.; Sharan, R.; Ruppin, E. The large-scale organization of the bacterial network of ecological co-occurrence interactions. *Nucleic Acids Res.* **2010**, *38*, 3857–3868. [CrossRef]
150. Market Reports. Global Nuclear Decommissioning Market—Analysis of Growth, Trends and Forecasts (2018–2023). Available online: https://www.marketreportsworld.com/global-nuclear-decommissioning-market-12343410 (accessed on 5 March 2022).