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High-Level Radioactive Disposal Policy in Japan: A Sociological Appraisal

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Abstract: This study critically appraises the Japanese government's high-level radioactive disposal policy by drawing on three sociological perspectives: risk society, sociology of scientific knowledge, and social acceptance. The risk society theory emphasizes that the Government of Japan and scientists under its control are pursuing nuclear power policy and repository siting within the conventional paradigm of the first modernity, which no longer aligns with the current reality of nuclear power utilization and its public awareness in Japan. Thus, a reflexive response from the policy side is essential to address the demands of a risk society. The sociology of scientific knowledge supports this view by demonstrating that, while scientists under governmental control attempt to convince the public of the safety of their geological disposal methods and the scientific validity of their siting procedures, these claims are largely a social construction of knowledge riddled with uncertainty and ambiguity about inherent environmental risks. The social acceptance standpoint also reveals a substantial bias in government measures toward ensuring distributive, procedural, and interpersonal fairness. Specifically, it critiques the heavy official reliance on monetary compensation to the host community, limited consideration of the allocation of intergenerational decision-making rights based on the reversibility principle, and the implementing agency's one-way asymmetrical risk communication for public deliberation.

Keywords: high-level radioactive waste; radioactive waste management; risk society; sociology of scientific knowledge; social acceptance; Japan

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1. Introduction

Various methods for the disposal of high-level radioactive waste (HLW) have been studied by relevant international organizations and countries [1]. Among these, geological disposal is technically feasible and accepted as the most viable disposal method worldwide as it can isolate HLW from the human living environment for more than 100,000 years. Japan, too, plans to conduct geological disposal [2].

Japan's management of HLW dates back to 1976 when the Japan Atomic Energy Commission (JAEC) established a goal and a research and development (R&D) policy to focus on geological disposal. Since then, R&D has been promoted by organizations such as the Power Reactor and Nuclear Fuel Development Corporation (PNC) (subsequently reorganized as the Nuclear Fuel Cycle Development Institute (JNC) in 1998 and integrated into the Japan Atomic Energy Agency (JAEA) in 2005). In 1992, the PNC issued the first progress report entitled the *Technical Feasibility of Geological Disposal*, which claimed that Japan would have the technical feasibility of geological disposal. With the accumulated results of more than 20 years of research, the JNC published the second report in 1999 entitled the *Technical Reliability of Geological Disposal for High-Level Radioactive Wastes in Japan—The Second Progress Report on Research and Development of Geological Disposal* (hereinafter referred to as the Second Progress Report) [3]. The report was submitted to the JAEC on 26 November 1999 [4]. The JAEC expected the report "to demonstrate the technical reliability of geological disposal in Japan and to provide a technical foundation for the selection of disposal sites and for the formulation of safety standards for promoting disposal projects" [5] (p. 1136). The

Specified Radioactive Waste Final Disposal Act was passed in the Diet in June 2000 and enacted as part of the development of legislation necessary to systematically implement the final disposal of HLW. The Nuclear Waste Management Organization (NUMO) was established in October 2000 to implement the HLW geological disposal [6], marking the beginning of the practical implementation of HLW disposal in Japan. The NUMO's responsibilities include "site selection, preparing relevant license applications and the construction, operation, and closure of the repository, as well as collecting fees from the owners of nuclear power plants" [7] (p. 1211).

Japan has pursued a reprocessing policy in its nuclear fuel cycle as opposed to direct disposal. This policy has influenced Japan's definition of nuclear fuel waste, with radioactive wastes generated by nuclear electric power generation generally classified into high- and low-level radioactive wastes [8]. The waste liquid generated during reprocessing is solidified using borosilicate glass, resulting in vitrified waste that is categorized as HLW in Japan [1]. Although HLW comprises less than 1% of the total radioactive waste volume, it accounts for more than 90% of the radioactivity of the entire radioactive waste stream [9]. On the other hand, low-level radioactive waste (LLW) is disposed of in shallow layers, such as the Rokkasho Low-Level Radioactive Waste Center, and includes radioactive waste containing transuranium elements (TRU) ("TRU waste"), which are classified as LLW. However, TRU nuclides have a long half-life [10] and, therefore, the disposal of TRU waste in deep geological formations was also added in 2008. As the NUMO does not possess research facilities, academic support is provided by the JNC (renamed in 2005 as the Japan Atomic Energy Agency: JAEA), other R&D institutes, and Japanese universities [2].

To the author's knowledge, partial or thematic reviews of social scientific work on HLW disposal policy in Japan have been conducted, but no comprehensive review of social processes involving planning, siting, and public deliberation has been compiled. Interrelated issues and common shortcomings are factors that dictate a range of policy processes; however, this academic gap hinders a sweeping glance at them. This study aims to fill this gap by drawing on pertinent sociological perspectives on long-term radioactive waste management. Content analysis, a technique widely used for analyzing textual data drawn from diverse sources including books, academic journals, policy reports, online news outlets, organizational websites, and other online media platforms, was employed in this study. The collected data were segmented into smaller units or chunks of text that underwent a meticulous coding process based on predetermined categories and themes. During the development of the coding scheme, relevant theoretical frameworks were identified and utilized to uncover the underlying patterns and meanings within the content. This iterative process of identifying key information and theoretical perspectives and their subsequent application for qualitative analysis facilitated a thorough comprehension of the research data.

The remainder of this paper is organized as follows. The next section introduces the theoretical and conceptual foundations. The third section provides an overview of the HLW disposal policy in Japan. The fourth section examines the process of a township application for conducting a literature survey on the siting of HLW disposal. The fifth section analyzes vital moments concerning government consultancy with a domestic epistemic community in the revision of the HLW disposal policy in Japan. Finally, the sixth section offers a discussion and conclusions.

2. Theoretical and Conceptual Underpinnings

The subject of HLW disposal in Japan is relevant to the following three sociological streams of thought related to risk perception and associated social action: *risk society*, *sociology of scientific knowledge (SSK)*, and *social acceptance*. Each of them is explicated as follows.

2.1. Risk Society

The risk society thesis, originally proposed by German sociologist Ulrich Beck, asserts that contemporary society has entered the stage of a "risk society" because of the materialization of an industrial society that generates environmental risks and dangers. Beck [11,12] argues that the rational pursuit of truth and progress through science, technology, and other social institutions has inadvertently led to the scale and scope of environmental risks that cannot be precisely calculated by science or readily minimized by technology. Contemporary social reality is overshadowed by environmental hazards that challenge the modernistic assumptions of rationality, computability, and progress. Thus, Beck observed that the optimistic trust and faith in science, technology, and other institutions, which also underpin the conventional notion of "sustainable development", have been crushed. Following the demise of the first modernity, the second modernity, which Beck dubs "reflexive modernization", emerges in ways that force individuals and societies to face the consequences of the first modernity, namely, environmental risks replete with uncertainty and doubt. As modern environmental problems are the outcome of advances in science and technology, social progress must be pursued by acting upon risks and accepting challenges, rather than simply relying on the ability of science and technology to eliminate them. Beck's risk society theory provides a reflexive perspective on social development, which in turn gives rise to the notion of "subpolitics". This involves promoting more democratic participation of ordinary citizens in decision-making processes, as opposed to solely relying on technocrats, experts, and business executives for control. By engaging in subpolitics, society can reorganize its approach to living under conditions of uncertainty and ambiguity.

2.2. Sociology of Scientific Knowledge

While the prevailing view of sustainable development and Beck's risk society thesis take a different stance to the position of scientific knowledge in contemporary society, neither approach sufficiently addresses "*how* scientific knowledge is generated and legitimated within hotly contested social contexts" [13] (p. 73, emphasis in original). In contrast, the SSK framework posits that the production of scientific knowledge is inherently a "*social* process" (ibid., emphasis in original) and, therefore, it scrutinizes the social construction of scientific knowledge. Through this lens, the SSK approach examines how specific scientists construct their claims as scientific facts, how such claims relate to the prevailing social circumstances, how they aim to persuade their peers of the validity of their claims, and how they convince lay people of the truthfulness and reliability of their scientific accounts. Moreover, the social construction of scientific knowledge is further complicated by the fact that scientists themselves are not detached from the social milieu in which they operate. They are influenced by a variety of factors, including pressure groups and concerned institutions whose interests they may be inclined to represent. Consequently, the constructivist approach regards the validity of scientific "truths" as agnostic, instead considering them as the product of complex social and institutional processes or as "social artifacts fabricated by social groups or institutions" [14] (p. 144).

Scientists have sought to measure and minimize environmental risks through environmental assessments and predictions based on mathematical modeling. Their objectivist assumptions imply that "risks and their manifestations are real, observable events" [14] (p. 144). However, the predictability and uncertainty of environmental risks can vary substantially. Some risks may go unnoticed simply because they are unforeseeable given the current state of available knowledge and monitoring technology [15]. As scientists rely on empirical evidence to formulate and conduct assessments, they may fall short of making accurate predictions when adequate evidence is lacking [16]. Furthermore, extreme natural disturbances are rare in populated areas, and long-term data may not always be available to build projections or extrapolations, rendering the accurate estimation of recurrence challenging. Under these circumstances, risk assessment becomes speculative at best [15]. Some risks remain unperceived due to a lack of acknowledgement. For instance, in the spring of 2008, the Tokyo Electric Power Services Co., Ltd. (TEPSCO), a subsidiary of the Tokyo Electric Power Holdings, Inc. (TEPCO), predicted that a potential tsunami with a maximum height of 15.7 m could strike the Fukushima Daiichi nuclear power plant, which was situated at 10 m elevation. However, the TEPCO disregarded this warning, and a catastrophe transpired in March 2011 following a tsunami with a height of 14 to 15 m [17]. Hence, Murphy (2010) posits that "perceptions of risk are social constructions that can be very different from risk itself where the processes of nature are involved" [15] (p. 281).

2.3. Social Acceptance

The phenomenon of social acceptance has been investigated in fields relating to technology and socio-technical systems. Upham, Oltra, and Boso [18] define acceptance as "a favorable or positive response (including attitude, intention, behavior and—where appropriate—use) relating to a proposed or in situ technology or socio-technical system, by members of a given social unit (country or region, community or town and household, organization)" (p. 103). Numerous social psychologists have studied nuclear power generation and HLW disposal as representatives of large, advanced science and technology systems to explore social acceptability [19]. The social psychology literature indicates that social acceptance of a technology or socio-technical system is strongly influenced by people's perceptions of fairness. In this regard, Besley [20,21] offers a useful conceptual framework, proposing that perceptions of decision-making regarding social acceptance are mediated by three kinds of fairness: distributive, procedural, and interpersonal.

In the realm of social acceptance, distributive fairness is concerned with the outcomes of a technology or socio-technical system, whereby a risk–benefit evaluation is conducted to determine if the benefits outweigh the risks. With respect to the social acceptance of nuclear technology, the benefits are widely distributed geographically and in various applied fields, such as health, food processing, infrastructure, and energy. Conversely, the risks associated with accepting a locally unwanted facility, such as an HLW repository, tend to be localized, and the public's perception of the magnitude of these risks can be significant. The negative connotations that are associated with nuclear-related facilities, characterized by their involuntary, unknown, delayed, new, uncontrollable, fatal, and catastrophic attributes, make nuclear-related risks rank highest among all considered risks [22]. Moreover, when an introduced technology or system is stigmatized, the areas that have accepted it are also stigmatized, leading to reactions that shy away from or avoid them. This environmental stigma is a matter of personal concern but has greater societal implications as it acts as a concern about evaluation or rumor [23].

Monetary compensation has long been used as a strategy to foster local acceptance of facilities that are unwanted by the community and to mitigate the associated costs incurred by those affected. The cost–benefit framework assumes that the success of such compensation depends on the extent to which it outweighs the negative consequences of the facility in question. However, scholars have pointed out that for facilities that pose potential environmental or health risks, focusing on compensation as a way to address the risks may be counterproductive and may even exacerbate the distrust of locals toward such facilities. In fact, compensation may be interpreted as a signal that the facility in question poses risks that would otherwise be considered negligible [22]. Additionally, concerns about the distribution of risks and benefits across generations may also arise, as the present generation may enjoy the benefits while imposing risks on future generations. This raises issues of intergenerational equity, which must be taken into account in designing compensation schemes [24].

Procedural fairness, as the second aspect of fairness, pertains to the equity of decision-making procedures, including the representation of citizens' voices in public hearings and other forums [21]. Research has demonstrated that procedural fairness can be even more significant than distributive fairness, as people are more likely to accept a decision when the decision-making process is perceived as fair, regardless of the outcome being unfavorable to them [25]. Hence, from the standpoint of procedural fairness, the framing of discussions concerning the final disposal of HLW is a crucial matter [24]. When accepting a geological disposal facility, citizens may acknowledge the need for an HLW geological disposal policy, but they may oppose the establishment of a geological repository in their communities. The phenomenon of "not in my backyard" (NIMBY) has become increasingly common in the siting of controversial facilities such as geological repositories, due to the potential high social risks posed to the local community. As such, it is critical to take procedural fairness into account in the decision-making process, in order to ensure that the community as a whole is able to accept the siting decision [23]. However, a mere appeal to technological safety would not suffice in enhancing the likelihood of local acceptance of HLW disposal, as citizens in Japan now perceive the issue as more of an ethical than technological risk, following the Fukushima Daiichi nuclear disaster [26]. Therefore, it is important for decision-makers to take into account the broader social, cultural, and ethical contexts in which the facility is being situated, and to ensure that local communities are meaningfully engaged in the decision-making process.

Procedural fairness becomes increasingly important in decision-making processes when the level of uncertainty regarding the outcomes and impacts of a decision increases. In cases where scientific assumptions made by experts to measure long-term safety become controversial or doubtful, the production of knowledge can no longer be perceived as a specialized task to be entrusted solely to scientists. Instead, it must be "democratized" by including the initiative of "extended peer communities" comprising all stakeholders and local citizens involved in the problem situation. This approach aims to improve the quality of knowledge of the natural and social world and, consequently, promote procedural fairness in decision-making. Therefore, procedural fairness is highly relevant to the debate on deliberative democracy, which underscores the importance of the inclusive involvement of people in discussing shared issues in appropriate deliberative arenas, and reaching democratic decisions based on fair and transparent procedures [27].

In addition to intragenerational equity in contemporary society, procedural fairness requires consideration of intergenerational equity, as expressed in the ethical principle of sustainable development [28]. The concept of "ethical acceptability" is employed to address the temporal dimension of acceptance, which requires reflection on the introduction of new technologies or systems from moral perspectives [29]. In the context of HLW management, risk considerations span tens of thousands of years, making it imperative to reflect on ethical norms concerning ultra-long-term risks [23]. It is, thus, clear that the issue of HLW management involves ethical dimensions that are critical to achieving not only social acceptance but also sustainable development. From an ethical standpoint, sustainable development requires that present generations communicate the risks and benefits of an introduced technology or socio-technical system to future generations, as seen through the lens of ethical acceptability [28]. This implies a reflexive approach to decision-making that prioritizes intergenerational equity, as outlined by Beck. Additionally, the intergenerational subjective norms of the present generation—stigma of perceptions as a polluted town due to the acceptance of HLWs—may further impede the present generation's willingness to accept a repository in their community [21].

Third, interpersonal fairness concerns individual perceptions of the interactive treatment they receive in their communication of organizational procedures. The conventional approach to risk communication in the public understanding of scientific issues follows a deficit model, where scientific knowledge is unilaterally transmitted from experts to the public, based on the perception that the public lacks scientific knowledge [30]. However, the public acceptance model of risk communication brings attention to a critical point: when lay people assess the acceptability of a controversial technology or risky socio-technical system, they may be more concerned with the trustworthiness and respectfulness of the risk communicators towards their views and values, rather than the performance or safety of the technology itself [31]. Effective risk communication plays a key role in shaping the public's perception of the efficacy and risks associated with a technology or socio-technical system, and in establishing trust. The distribution of risks, benefits, and stigmas is also influenced by the level of trust that is either gained or lost [25]. In order to ensure interpersonal fairness in risk communication, it is essential to engage in a two-way symmetrical communication of risk, which allows experts and citizens to engage in co-thinking on an equal footing [24,32]. This approach is vital in establishing a forum for dialogical communication, enabling the exchange of views on self-interests and reasons to achieve the common good [27]. This approach ensures "democratic deliberation" between experts and lay people, as it promotes equal participation and shared decision-making.

3. Overview of HLW Disposal Policy in Japan

This section comprehensively reviews the fundamental policies and procedures formulated by the government concerning the HLW disposal. The discussion encompasses an assessment of the Second Progress Report and concrete geological disposal methodologies. Additionally, the investigation delves into strategies for minimizing waste and procedures for selecting suitable sites for disposal repositories, including both local siting protocols and nationwide mapping approaches.

3.1. Second Progress Report

The Second Progress Report is a voluminous document comprising several volumes and supplementary material, totaling over 2400 pages. The report was developed with the primary objective of demonstrating the technical reliability of geological disposal in Japan. To achieve this, the JNC outlined a comprehensive goal of verifying the existence of rational and viable technologies for HLW disposal and demonstrating, on scientific grounds, that such technologies and an appropriate geological environment would ensure long-term safety. To this end, the report summarizes the outcomes of the three main research and development fields pursued by the JNC. First, it sought to identify critical geo-environmental conditions that are relevant to geological disposal by conducting a "research study on geological environmental conditions". This information was used as input data for the design and assessment of the disposal site. Second, through "R&D of disposal technology", the JNC aimed to examine the specifications of the artificial barrier and the layout of the disposal site, taking into account a wide range of geological environments in Japan, while demonstrating the engineering feasibility of geological disposal. Finally, the JNC aimed to ensure the long-term safety of geological disposal by conducting "performance evaluation research". This research aimed to establish a method for evaluating a geological disposal system constructed based on specific geo-environmental conditions, population barrier specifications, and disposal site layouts [33].

The final chapter of the General Report presented an overview of the technical advances attained as a result of the comprehensive R&D endeavors. The report affirmed that the following foundations had been laid:

- A geological environment that satisfied the prerequisites for the geological disposal concept existed extensively across Japan, and a novel approach was devised to appraise if a specific geological environment fulfilled these criteria.
- Techniques were formulated to effectively design and construct artificial barriers and waste repositories that could adapt to diverse geological and environmental conditions.
- A method was devised to predict the long-term safety of geological disposal, which was thoroughly verified for its safety and efficacy [33] (p. VII-3).

Before its submission, an international peer review of the English version of the report was conducted by the Nuclear Energy Agency (NEA) to ensure its rigor and quality [26]. The Ministry of International Trade and Industry (now known as the Ministry of Economy, Trade and Industry: METI) has boasted that the technical reliability of Japan's geological disposal is guaranteed through a meticulous series of processes [24].

3.2. Geological Disposal Methods

A distinctive feature of HLW is the danger it poses to the human body because of the strong radioactivity it emits. Immediately after production, the vitrified material emits a staggering 1.5 million millisieverts of radiation per hour, equivalent to 150,000 X-ray CT scans, and has the potential to cause death within mere 20 s [34]. This high level of radioactivity is primarily caused by fission products (e.g., cerium-144, cesium-137, and strontium-90) contained in HLW that have relatively short half-lives of several decades. The radioactivity level of these fission products gradually decreases over time, with only one out of several thousand [8] or approximately 1/10,000 remaining after 1000 years from the vitrification process [34]. Subsequently, the low-level radioactivity of actinides such as plutonium and americium persists for an extended period [8]. It can take up to 100,000 years for the vitrified material to reach the same level of radioactivity as natural uranium ore [34]. As a result of its extended radioactivity, TRU waste is also planned to be geologically disposed of together with HLW [8].

The long-term effectiveness of the deep-burial disposal method depends on the stability of the stratum [35]. In Japan's geological disposal program, HLW will be buried in an old stratum deeper than 300 m below ground, which has been carefully selected to avoid active faults and volcanic areas [3]. To ensure the safety of human populations for more than 100,000 years, a "multiple barrier system" has been designed, consisting of both "artificial" and "natural" barriers. The former involves enclosing the vitrified waste generated in the reprocessing process within a steel container called an "overpack", which is approximately 20 cm thick, and then covering it with a layer of bentonite clay that is approximately 70 cm thick. The "natural barrier" simply refers to the bedrock and underground environment [36]. The vitrified HLW is stored in stainless-steel canisters, which are specifically engineered to confine radionuclides and prevent immediate dissolution upon contact with groundwater [5]. To further ensure long-term safety, the canisters are surrounded by an iron overpack, which acts as a shield against radiation and also serves to prevent any contact between the vitrified waste and groundwater. The overpack rusts over time, thereby creating a state of reduction in which radioactive elements become less soluble, further reducing the risk of radioactive release into the environment. As a material, clay bentonite is endowed with the ability to expand and fill gaps, fractures, and pores within the bedrock upon contact with groundwater, thus preventing further intrusion of water. Its clay composition offers an added advantage of adsorption, which can effectively suppress the diffusion of radionuclides in the event of leakage [36]. Nonetheless, in cases where radionuclides manage to escape beyond the bentonite layer, minerals within the bedrock will adsorb the radionuclides, and the slow movement of groundwater will limit their migration. Consequently, radionuclides carried by the groundwater will be gradually dispersed and diluted, thus averting any potentially hazardous outcomes [4].

3.3. Waste Reduction

The HLW remaining after the reprocessing of spent nuclear fuel comprises minor actinides (MA) and fission products (FP), which cannot undergo further reprocessing [37]. The term MA refers to a group of ten actinide elements with atomic numbers greater than that of uranium (U, atomic number 92) but does not include plutonium (Pu, atomic number 94). The MA group includes radioisotopes with half-lives ranging from thousands to millions of years, such as neptunium (Np-237 with a half-life of 2.14 million years), americium (Am-242 with a half-life of 7400 years), and curium (Cm-245 with a half-life of 8500 years). Some plutonium isotopes also possess long half-lives (e.g., Pu-239 with a half-life of 24,000 years, Pu-240 with a half-life of 6500 years, and Pu-242 with a half-life of 380,000 years). The process of reducing the long-term hazards of long-lived transuranic elements by fissioning these MAs in nuclear reactors is known as nuclear transmutation. Plutonium has been the only transuranic element to be extensively recovered from spent fuel and utilized as a resource [38]. The R&D of nuclear transmutation presents a vital challenge for the disposal of HLW, as its practical implementation could significantly decrease the management period of HLW [35]. Furthermore, proponents of transmutation argue that it could reduce the quantity of waste sent to geological repositories by as much as 1/100th of the amount that would be produced by the direct disposal of spent fuel.

Nonetheless, a report issued by the US National Academy of Sciences in 1996 suggests that removing 99.5% of the sludge could take at least 150 to 200 years, even with the use of many fast reactors, and thousands of years if light–water reactors are employed [39]. Certain experts in Japan hold a pessimistic view regarding the feasibility of transmutation, considering the limited success of fast reactor development in Japan and other countries. For instance, Professor Emeritus Shibata [35], a renowned radiation scientist at the University of Tokyo, expressed doubts regarding the viability of this technology by stating, "Although I do not deny that the technology to convert ultra-long-lived nuclides in radioactive waste into short-lived nuclides has some room for future research, I do not think it promising" (p. 129).

3.4. Geological Disposal Siting

3.4.1. Local Siting Procedure

Upon its establishment, the NUMO recognized the critical importance of acquiring candidate disposal sites through the voluntary application of local communities, in order to advance the project in a seamless and productive manner. In view of this, the NUMO adopted an open recruitment system to ensure transparency and fairness in the selection process [3].

According to NUMO documents, landfill site selection proceeds in three stages (Figure 1). First, upon receiving an application from the mayor of a township, the NUMO conducts a survey using various resources, such as ancient writings, historical records of past natural disasters (e.g., earthquakes, tsunamis, and volcanic activity), and the intentions of the concerned municipality and prefecture. This preliminary phase is referred to as a literature survey. Following this, if the results of the survey show no signs of concern and the consent of the relevant governments is obtained, the area is deemed a "preliminary survey site". In the subsequent "outline survey", further investigations such as drilling and bowling are conducted to verify the underlying geological conditions. Based on the findings from the outline survey, the intentions of the concerned local governments are confirmed, and areas that pass this stage are selected as "detailed survey sites", where research facilities are constructed underground for detailed geological investigations. If no issues are identified, and the intentions of the relevant local governments are confirmed, the area is selected as the final disposal construction site [40].

In December 2002, a public call for proposals was initiated to select a preliminary survey area to identify a geological disposal site. According to the call for proposals, a literature survey of the application area was supposed to be conducted and an outline survey area selected by 2008, following which the construction of the final disposal site was planned to commence around 2028, and the final disposal was set to commence in 2038 [41].

3.4.2. Nationwide Map

After deliberations by the *Radioactive Waste Working Group* ("Waste WG") in May 2015, the METI revised the *Basic Policy on Final Disposal of Specified Radioactive Waste* (Cabinet decision). During this process, the national government proclaimed that it would "stand at the forefront" in the selection of the NUMO's general survey area, and identified scientifically promising areas that were highly evaluated as being scientifically suitable. By doing so, the government sought to gain the understanding and cooperation of the national population and local residents and made a request to the relevant local governments to consider HLW disposal in their areas [42]. As a response, in April 2017, the *Geological Disposal Technology Working Group* ("Technology WG") compiled the requirements and standards for presenting the scientific characteristics of the region, and in July 2017, the Agency for Natural Resources and Energy of the METI released the *Nationwide Map of Scientific Features for Geological Disposal* ("Nationwide Map") [30]. Since then, the NUMO has conducted geological disposal briefing sessions throughout Japan using detailed materials based on the map [34].

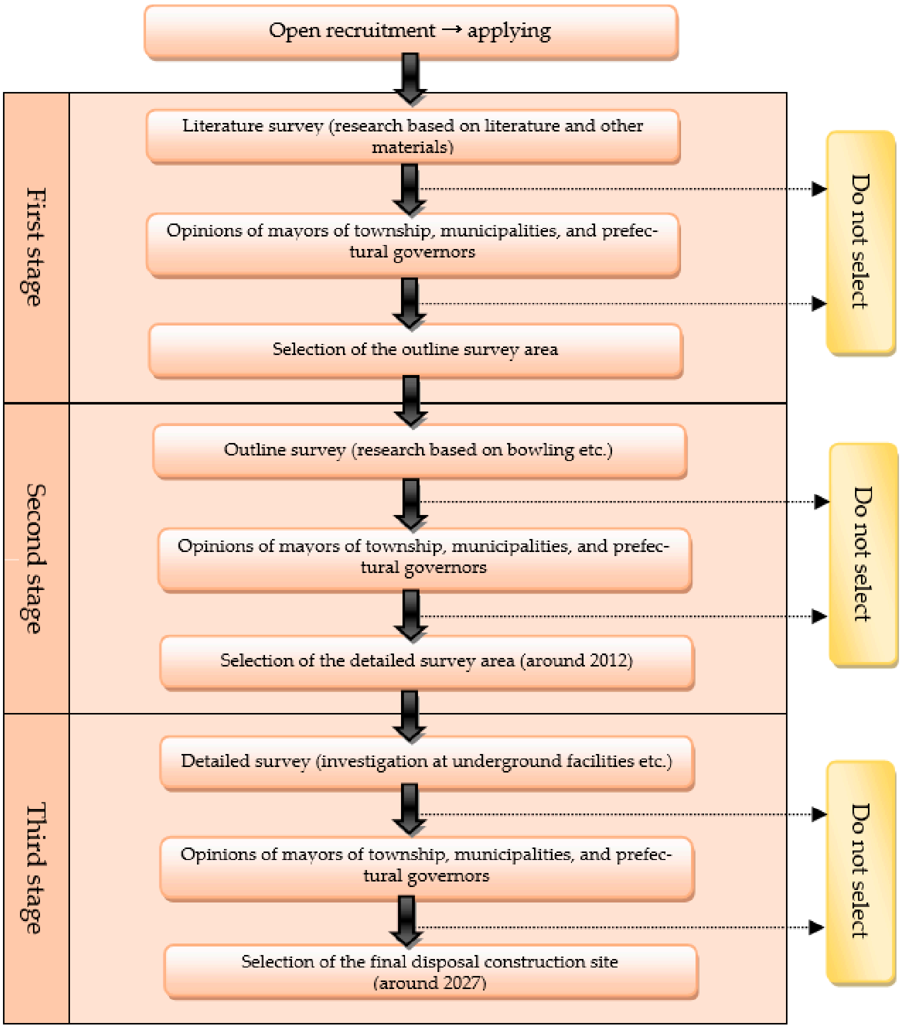

Figure 1. The selection process of HLW disposal site. Source: modified from [19].

The Nationwide Map, with a scale of 1/2,000,000, classifies Japan's entire region into four groups:

(a) Areas assumed to have unfavorable characteristics concerning long-term stability deep underground (orange);
(b) Areas estimated to have unfavorable properties regarding future drillability (silver);
(c) Areas with a relatively high probability of confirming favorable characteristics (green);
(d) Areas among (c) that are also advantageous in terms of waste transportation (dark green) [43] (Figure 2).

The map eliminates unfavorable regions that meet eight requirements, such as areas containing active faults, volcanoes, or mineral resources. Furthermore, coastal areas situated within 20 km of the coast, which make it easier to transport nuclear waste from storage facilities, were deemed preferable areas (Table 1). Consequently, of the approximately 1750 municipalities in Japan, approximately 900 were identified as areas with a high possibility of safe disposal [44].

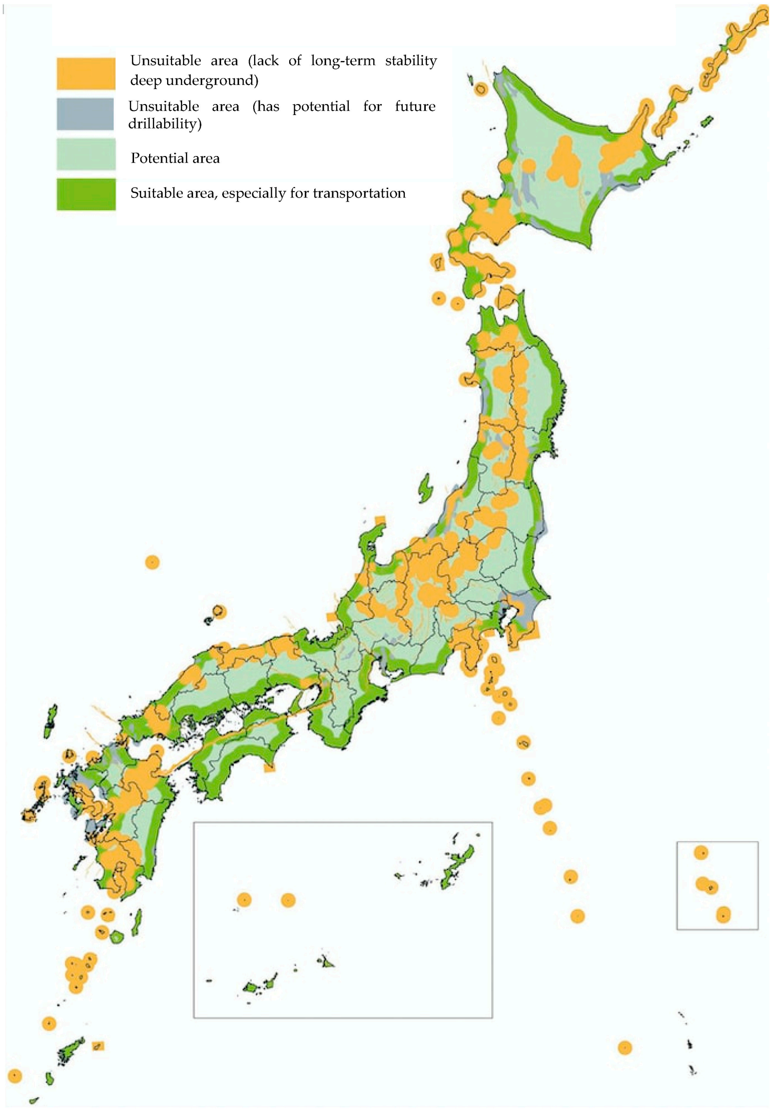

Figure 2. Scientific Nationwide Map. Source: [44].

Table 1. Requirements and Criteria for Scientific Characterization Maps.

Requirements/Criteria for Unfavorable Areas		
	Requirements	**Criteria**
Volcano/ Pyrogenesis	The surrounding areas of volcanoes (preventing magma from penetrating the repository)	Within 15 km radius from the center of the volcano
Fault activity	Areas where the impact of active faults is large (preventing destruction of disposal sites related to a fault slip)	Within a certain distance (fault length × 0.01) on both sides of a major active fault (fault length of 10 km or more)
Uplift/erosion	Areas where large erosion is expected to occur in the future due to the upliftment and lowering of the sea level (preventing disposal sites from approaching the ground surface)	A coastal area with a large amount of upliftment in the past, with the possibility of uplift exceeding 300 m in 100,000 years
Geothermal activity	Areas with strong geothermal heat (preventing functional deterioration of artificial barriers)	Geothermal gradient greater than 15 °C/100 m

Table 1. *Cont.*

Requirements/Criteria for Unfavorable Areas		
	Requirements	**Criteria**
Volcanic hot water/deep fluid	Areas with highly acidic groundwater (preventing functional deterioration of artificial barriers)	pH 4.8, etc.
Soft ground	Areas where the landfill stratum is soft (preventing collapse accidents of underground facilities during construction and operation)	The stratum from about 780,000 years ago is distributed deeper than 300 m
Effects of pyroclastic flows, etc.	Places where pyroclastic flows can reach (preventing destruction of ground facilities during construction and start-up)	Pyroclastic flows from about 10,000 years ago are distributed
Mineral resources	Areas where mineral resources are distributed (preventing human intrusion associated with resource mining)	Rich in coal, petroleum, natural gas, and metallic minerals
Requirements/Criteria for Desirable Range		
	Requirements	**Criteria**
Shipping	Areas where surface transport from the coast is easy	Approximate distance of within 20 km from the coast

Source: [43].

4. Township Application for Literature Survey

The process of selecting HLW disposal sites in countries with nuclear power plants has faced numerous obstacles and Japan is no exception to this trend [45]. As discussed, this is because the HLW geological repository is a typical NIMBY facility. The approval and acceptance of these sites can result in reputational damage and social stigma for future generations [46]. Furthermore, the current administrative law in Japan stipulates that only one final disposal site can be selected throughout the country [45], which may have fostered a sense of NIMBYism among local communities.

4.1. Toyo Town, Kochi Prefecture

In January 2007, Toyo Town of the Kochi Prefecture expressed its interest in participating in the open recruitment process for selecting the preliminary survey area for the HLW disposal site. However, the town withdrew from the process just two months later, on 5 April 2007. Moreover, despite reports that 14 municipalities were considering applying for the recruitment, they did not actually follow through with their applications [47]. By analyzing the reasons and processes that led to the application and withdrawal of Toyo Town, one can gain insight into the limitations of the current recruitment system. Toyo Town, located on the border of the Kochi and Tokushima Prefectures, had a population of 2070 as of 1 November 2022, which has decreased from approximately 3300 in 2007. In the summer of 2006, with an aging rate of about 40%, a welfare recipient rate of over 6%, and a financial strength index of 0.14 (fiscal 2004 figures), the mayor of Toyo Town, Yasuo Tashima, along with town council members and executives, initiated a study session to consider the location of the HLW disposal site.

In August 2006, the initial subsidy for applicants to the outline survey area was increased from JPY 200 million to JPY 1 billion. However, in September of the same year, a campaign against the application was launched by professional surfers from Toyo Town, and Governor Hashimoto of the Kochi Prefecture also expressed opposition to it. In October, the *National Volunteers Who Love Ikumi Coast*, formed mainly by the above-mentioned surfers, and the *Association for Thinking about Toyo Town*, formed by the residents of Kaiyo town, Tokushima Prefecture, actively protested against the plan. In December, these associations submitted petitions and signatures from over 60% of the town's population to express their dissent. Under such circumstances, Mayor Tashima made a political decision and submitted an application to NUMO on 25 January 2007. In February, concerned residents submitted a direct request for the enactment of an ordinance refusing to bring in HLWs, and in March, a request for the dismissal of the mayor was submitted to the town election management committee. On 22 March, the town passed both the ordinance on refusal to bring HLWs into the town and the ordinance on the referendum. As a result, the mayor resigned on 5 April, and a new mayoral election was held on 22 April [40]. The election yielded a resounding victory for Mr. Sawayama, who opposed the HLW application, receiving 1821 votes (71% of the votes). In contrast, former mayor Tashima lost by a large margin of 761 votes, receiving only 29% of the votes [19]. Consequently, the application was officially withdrawn the day after the election [40]. Of the 2989 valid voters in the town at the time, the voter turnout was about 89%, and the pre-voting rate was remarkably high at 27.8% [19].

In September 2007, METI made an announcement that it would consider the option of national government offers to municipalities, in conjunction with the NUMO's open recruitment initiative [40].

4.2. Suttsu Town and Kamoenai Village, Hokkaido Prefecture

In August 2020, Suttsu Village Mayor Haruo Kataoka of the Hokkaido Prefecture expressed his intention to accept the literature survey, 13 years after Toyo Town withdrew its application. The official application for the literature survey was submitted in October 2020. The decision to move forward with the survey stage was prompted by the tight financial conditions of the town, and the mayor's efforts to explore potential solutions, including the possibility of hosting an HLW geological repository. To gain a better understanding of the issue, the mayor invited a lecturer from the NUMO and organized a study session about HLW disposal in June 2020. During the session, he learned that it was possible to withdraw from the survey stage, if necessary, which influenced his decision to apply [48]. In September 2020, the mayor expressed willingness to proceed to the third survey stage, which spans 16 years and involves a detailed survey. It is worth noting that, although the amount of government subsidies for the third stage is yet to be determined, the total amount of subsidies until the third stage could be paramount. Subsidies for literature surveys are offered by the national government for a maximum of two years, with a cap of JPY 2 billion. The second survey stage provides a maximum of JPY 7 billion to the target site over a period of four years [49].

In a similar vein, Kamoenai Village, with a population of 820 located in close proximity to Suttsu Town, also expressed interest in conducting a literature survey. The village's Chamber of Commerce and Industry submitted an application for the survey to the village committee in October 2020, which was subsequently accepted [50]. The survey commenced in November 2020, and as of November 2022, 760 material items had been collected, with analysis and compilation ongoing [51]. The JPY 2 billion allocated for the conduct of a literature survey is primarily received by the local governments of the survey sites, with more than half of the amount going to these entities and the remaining portion being distributed to nearby municipalities and prefectures. However, despite the incentives, three of the four neighboring localities of Suttsu Town, namely Rankoshi Town, Kuromatsunai Town, and Shimamaki Village, refused to accept the literature survey and declined to receive the subsidies [50]. Iwanai Town was the only town that announced its acceptance, explaining that it was "highly useful for regional development". Meanwhile, in the vicinity of Kamoenai Village, two towns and one village (Furubira Town, Kyowa Town, and Tomari Village) received it, whereas Shakotan Town declined [52]. In Hokkaido, there is a "Nuclear Free Ordinance". Governor Suzuki, who vocally opposed the acceptance of nuclear waste, urged both Suttsu Town and Kamoenai Village to abide by the ordinance [34]. Consequently, the Government of Hokkaido also declined to receive the offer of subsidies [52].

In parallel with the literature review, meetings were held in Suttsu Town and Kamoenai Village, organized by the METI and the NUMO, to discuss HLW disposal issues with residents from various standpoints, including the progress of the literature review. These meetings are held for approximately two hours in the public hall of their areas, with committee members representing the area participating in dialogue with NUMO officers and MCs through a facilitator. In Suttsu Town, a maximum of 16 committee members participated in 15 meetings between April 2021 and February 2023. In Kamoenai Village, 15 meetings were held from April 2021 to March 2023, with a maximum of 18 committee members participating. In May 2022, a symposium was held in Kamoenai Village with the participation of 74 villagers [53].

From a scientific standpoint, there has been mounting opposition to the geological disposal of nuclear waste in the regions surrounding Suttsu Town and Kamoenai Village. In October 2021, a statement was issued by geologist Satoshi Okamoto and three other scientists, along with 62 volunteers, contending that the areas in question were not appropriate for such disposal. Their argument was based on several factors, including the composition of the strata around Suttsu Town, which consist of soft sedimentary rocks and hyaloclastite rocks that are highly susceptible to cracking and fissures. Moreover, most of the lands in Kamoenai Village lie within a 15 km radius of Mt. Shakotan, a quaternary volcano, making the area unsuitable for geological disposal according to the Nationwide Map. Furthermore, as in the case of Suttsu Town, the stratum at the southern end of Kamoenai Village, which is considered a slightly more viable site, is also composed of hyaloclastite rocks. In addition, an active fault zone that stretches over a length of more than 32 km from Suttsu Town to Oshamanbe Town, as well as an active fault with a total length of over 20 km off the coast of Enai Village, further highlight the unsuitability of the region for nuclear waste disposal [54].

5. The Government Consultancy with Domestic Epistemic Community on HLW Policy Redirection

In 2012, when no progress was taking place in identifying potential candidate sites for the literature survey, the Policy Evaluation Subcommittee recommended that the JAEA request the Science Council of Japan to deliberate on the issue, with the aim of actively seeking opinions and views from a wide range of third-party and highly independent academic agencies [52]. In response to the request, the Science Council issued a document in September 2012 entitled *Responses: Regarding the High-Level Radioactive Waste Disposal* ("2012 Responses"), which contained six key responses (Table 2).

Table 2. The six responses included in the 2012 responses document.

(1)	The fundamental review of the policy on the disposal of high-level radioactive waste;
(2)	Recognizing the limits of scientific and technological capabilities and ensuring scientific autonomy;
(3)	The reconstruction of the policy framework based on temporary storage and total quantity management;
(4)	The necessity for persuasive decision-making procedures for the equity of burden;
(5)	The necessity for multistage consensus-building procedures in establishing forums for discussion;
(6)	Recognition that problem solving requires persistent long-term efforts.

Source: [55].

In April 2015, the Science Council published a policy proposal document titled *Policy Recommendations for Disposal of High-Level Radioactive Waste: Temporary Storage for National Consensus-building* ("2015 Recommendations"). It contains 12 proposals aimed at facilitating the implementation of the proposals presented in the 2012 Responses [56] (Table A1 in Appendix A).

Thus, the Science Council made many proposals in the 2012 Responses and the 2015 Recommendations, but not all were adopted by the government. Several crucial proposals were not given due attention, including three primary points. The first point concerns the government's failure to recognize the interconnectedness between nuclear power policy and the selection of disposal sites. The 2012 Responses criticized Japan's nuclear policy for its inverted procedure in which the government sought to establish a national consensus on individual policies regarding HLW final disposal site selection before obtaining a national consensus on the overall policy on nuclear power generation, a flaw that persisted even before the Fukushima Daiichi nuclear accident. In light of this, the Science Council proposed the introduction of basic concepts such as "temporary storage" and "total quantity management" to facilitate overall consensus-building before moving on to individual consensus-building [55]. The concept of temporary storage has been proposed to secure a moratorium period of several decades to several hundred years, during which appropriate measures can be established to deal with the problem. Unlike interim storage, which is designed to facilitate the eventual geological disposal of high-temperature vitrified waste generated after reprocessing, temporary storage aims to provide a pause for the exploration of alternative disposal methods, including those that do not involve geological disposal [34]. The 2015 Recommendations propose a specific temporary storage period of 50 years, divided into 30 years for consensus-building and site selection for geological disposal, and 20 years for the construction of a disposal site [56].

The concept of total quantity management is integral to Japan's approach to dealing with HLWs. As defined in the 2012 Responses, it entails monitoring and limiting the total quantity of HLW to a desirable level. There are two ways to achieve this: setting an upper limit on the total amount based on the progress of nuclear phase-out and controlling the increase in the total amount of HLW generated per unit of power generation [55]. Total quantity control is, thus, intended to prevent the unchecked expansion of nuclear power plants and the resulting increase in HLW generated. As Sweden, a global leader in HLW disposal, has no strong correlation between nuclear policy and disposal site selection, the Japanese government maintains that both policies can be implemented in parallel while promoting consensus-building [34]. The 2015 Proposals further highlighted that the government's efforts towards expanding the capacity of interim storage were not accompanied by policies aimed at implementing the concepts of temporary storage or total quantity management [56]. Recent developments have gone against the recommendations put forward in the 2012 Responses proposal. Specifically, on 28 November 2022, the METI announced a concrete policy for rebuilding and replacing nuclear power plants that were to be decommissioned, thereby effectively reversing the government's earlier commitment to reducing reliance on nuclear power as much as possible [57].

Second, the HLW disposal policy of "the government taking the lead" may hinder the Science Council's advocacy of the "autonomy of scientific research" conducted by "independent groups of scientists" and "consensus-building through a fair and neutral discussion process". Following the 2012 Responses, the JAEC released an opinion entitled *Future Measures for Geological Disposal of High-Level Radioactive Waste* in December 2012, wherein five proposals were put forth to the government. One of the key proposals recommended that the government take charge of restructuring future nuclear energy policy, which was based on the lessons learned from international precedents. Following international precedents, the proposal recommends the creation of a third-party organization that would oversee the efforts of the operational body responsible for HLW disposal and encourage the government and the operational body to make appropriate improvements [58]. This proposal is based on the recognition that current scientific knowledge of the ultra-long-term safety and risks associated with HLW disposal is incomplete. The proposal is in line with the suggestions put forth in the 2012 Responses, which called for the creation of a "forum for professional deliberation by an autonomous group of scientists (epistemic community)" [55] (p. 19) and the establishment of "multi-stage forums for discussion in which various stakeholders participate" coordinated by a "third party in a fair position" (ibid., p. 20). To this end, the Science Council of Japan proposed the creation of a *National Council on Nuclear Waste Issues*, emphasizing public participation, and a *Fair and Neutral Expert Investigation Committee for Examining Scientific and Technological Issues*, comprising relevant experts, in the 2015 Recommendations [56].

Thus, the proposal for the government to take the lead in restructuring nuclear energy policy does not imply that the government should unilaterally determine and implement nuclear power policy. Rather, it entails the government's involvement in reconstruction, which includes the review of laws and systems, in collaboration with various stakeholders, such as citizens, local governments, electric power companies, and operational bodies. Despite this, the government is expected to take overall responsibility for the entire reorganization. Nevertheless, in May 2013, the METI established the Waste WG to deliberate on the final disposal of HLW and announced that the government would assume a leading role in addressing the issue [30]. In December 2013, while discussions were still ongoing, the *Conference of Ministers Concerning Final Disposal* made an abrupt decision regarding policy and promptly reported it to the Waste WG. Consequently, the Waste WG has been relegated to the role of a "subcontractor organization", largely subservient to the government's will [59]. Meanwhile, the establishment of the Technology WG by the METI's *Comprehensive Energy Research Committee* in October 2013 appears to contradict the 2012 Responses' call for an open, third-party organization consisting of autonomous groups of scientists. The lack of these characteristics raises concerns about the impartiality and independence of the WG.

The third issue concerns the selection process for potential disposal sites, which continues to prioritize profit over other factors. This can be attributed to the inflexible policy that isolates the disposal site selection process from the overall nuclear power policy and fails to establish an independent and impartial organization to build consensus. In the aftermath of the Fukushima nuclear disaster, which severely eroded public confidence in Japan's nuclear power policy, the government may have to continue offering economic incentives to attract potential sites for HLW disposal, if it intends to adhere to the traditional consensus-building approach. However, the Science Council of Japan points out in its 2012 Responses that it is unfair to burden those who prioritize safety and risk concerns with the responsibility of financially resolving the disparities between the power generation beneficiary areas, such as metropolitan areas, and the sparsely populated areas proposed as candidate sites for HLW disposal. It also suggested that the larger the size of the financial compensation, the greater the danger felt by people [55].

The Science Council proposed a series of measures to prevent the use of financial means as the primary driver for site selection, including the transfer of some functions of the government and power companies to the disposal area selected for relatively stable geological strata, the construction of a facility to store important data, and the establishment of a large-scale research base related to nuclear radioactive waste at the disposal area [55]. A case in point is the Forsmark disposal site in Sweden, where the mayor of the local city of Estommar shared a positive vision with citizens that the city would be reincarnated as an industrial area where various high-tech facilities would gather, resulting in the acceptance of the disposal site by the citizens [34].

6. Discussion and Conclusions

The scientific community is divided on whether the Second Progress Report provides sufficient evidence to support the existence of suitable geological conditions for HLW disposal and its technical feasibility. Of critical concern is the fact that the findings presented in the report cannot be independently verified, thereby undermining confidence in the safety of geological disposal and stability of the underlying strata at any given site.

According to Ishibashi [60], a geologist who served on the drafting committee for this report, when he remarked at a meeting that the conclusion of the report was improperly worded, he was told that the language used in the conclusion had already been decided and could not be altered. Additionally, when Fujimura [5] presented a critical review of the Second Progress Report, he was told that its original intent was to "provide technical sources of judgment to advance the geological disposal plan from the R&D stage to the implementation stage". Thus, his critique was deemed as one that did "not understand the objective of the Second Progress Report" (p. 1136). The stated goal of the nuclear energy policy, which is to shift geological disposal from the R&D stage to the implementation stage, must not undermine the possibility of independent scientific investigation or lead to "self-made alibi maneuvers" [60] (p. 70). It is noteworthy, however, that the report was published over ten years before the Fukushima Daiichi nuclear accident; the JNC's somewhat dogmatic inclinations were consistent with the Japanese nuclear power administration's propagation of the safety myth that accidents would "never occur at any nuclear power plants in Japan" [5] (p. 1136). Through a constructivist lens, this tendency among experts hired by the JNC can be interpreted as perceiving propositions that are transformed into political goals as "scientific truth".

Regarding the social acceptance of an HLW disposal site in a given locality, the current plan assumes that the HLWs generated through reprocessing will be disposed of after being stored in interim storages. Unlike this plan, the Science Council proposed that the government consider adopting a 50-year period of temporary storage, together with total quantity management, beyond interim storage. Although the Science Council did not suggest considering any broader options, it is possible to expand the scope of the HLW disposal process by incorporating the notions of reversibility and retrievability into the storage system. The International Atomic Energy Agency (IAEA) [61] defines reversibility as "the ability to reverse one or a series of steps in repository development at any stage of the program. This implies the review and re-evaluation of earlier decisions, as well as the technical means to reverse previous steps" (p. 4). Retrievability, on the other hand, refers to "the ability to reverse the action of waste emplacement" (ibid.), and is considered a special case of reversibility.

While many OECD/NEA countries using nuclear power have assumed retrievability through means such as above-ground temporary storage, France has been at the forefront of discussions surrounding the concept of reversibility. French nuclear energy policy incorporates the notion of "reversible geological disposal", whereby the disposal project will be implemented gradually. Based on the knowledge available at each stage, the design of the disposal site will be adapted from technological, environmental, economic, and social perspectives, and the deposited wastes will be retrieved. The period for ensuring reversibility in a geological disposal project in France is at least 100 years, until the disposal site is closed. This concept reflects a more flexible approach designed to leave options for future generations [62]. However, there is criticism that such flexibility shifts the managerial responsibility of the present generation, which has benefited from the technology that generates HLWs, to future generations [34]. However, a historical case study provides a cautionary tale. The Maxey Flats study in 1962 projected minimal movement of buried plutonium over a span of 24,000 years, leading to the approval and construction of the repository. Yet, the plutonium was discovered to have migrated two miles off-site in just ten years of operation, leading to a costly cleanup operation that reached $50–$85 million [63].

Although Japan's pursuit of a nuclear fuel cycle policy using fast reactors is questionable in terms of its rationality and feasibility [64], the Japanese government, following in the footsteps of France, has not abandoned its efforts to realize this policy. The use of fast reactors can potentially reduce the volume of HLWs through the process of nuclear transmutation once they are successfully developed and implemented. Additionally, a geologically safer area than the specific site used for HLW disposal may be identified, and the retrieved HLW may be transferred to that area. Furthermore, alternative disposal methods may prove to be superior to geological disposal.

Finland and Sweden are often cited as successful examples of social acceptance of the irreversible geological disposal method for HLWs. However, the geological stability of the strata in these Nordic countries is markedly different from that of Japan. Finland and Sweden are situated on the Baltic Shield, an area comprised of very old rocks from the Precambrian period, which provides a relatively stable geological environment [34]. In contrast, Japan has a history of crustal movements, including faults that occurred during the fourth geological period, approximately 1.7 million years ago, resulting in frequent small earthquakes and volcanic activities. The presence of cracks in rocks from these movements increases the risk of leaching and dissipation by groundwater, which must be minimized in radioactive waste disposal [65]. In light of public concern regarding the feasibility of ensuring safe geological disposal of HLWs for 100,000 years in Japanese strata with current scientific and technological capabilities, providing greater freedom of choice could foster greater procedural fairness, intergenerational equity in decision-making, and potential social acceptance in specific regions. Moreover, from the perspective of ethical acceptability, Matsuoka, Inoue, and Choi [66] maintain that refraining from making the final decision on the disposal method by the present generation, in a way, exhibits the fulfillment of their responsibility towards future generations.

The Waste WG's Radiation Waste WG Interim Report [67] made numerous references to the importance of reversibility and retrievability and examined their significance. However, the discussion was cut short after the government proposed changing the Waste WG's agenda to focus on presenting scientifically promising sites. Furthermore, in the Technology WG's interim and final reports [68,69] on the selection of scientifically promising disposal sites, there was no mention of reversibility or retrievability. The lack of attention given by scientists to reversible geological disposal may be linked to the government's eagerness to determine the repository site more quickly through its Nationwide Map [70].

The Nationwide Map in Japan shows numerous areas that are deemed suitable for geological disposal. The green-shaded areas are the ones that can be surveyed for the selection of disposal sites, although the Technology WG cautions that such regions do not necessarily ensure "the long-term stability of deep underground, and a detailed field survey is necessary to confirm the suitability of the construction site" [70] (p. 72). However, it has been criticized that the classification of the Nationwide Map is inadequate in identifying regions with undesirable characteristics. For instance, the Nationwide Map sets the radius of 15 km from a volcano, which is within the range of general volcanic activity, as one of the "unfavorable areas". However, Kogi [34] points out that this is only for known volcanoes and it is insufficient because it does not consider the possibility of unknown volcanoes. It is worth noting that the eastern side of Japan's volcanic front, which faces the Pacific Ocean, has been devoid of volcanic activity for several million years. Meanwhile, the western side of the volcanic front facing the Japan Sea has witnessed active volcanoes for hundreds of thousands of years. Even areas that are 100 to 200 km away from the front, such as the Mt. Unzen and Fukue volcanoes in Kyushu, and the Mt. Rishiri and Watari-oshima in Hokkaido, have active volcanoes. This suggests that the emergence of a new volcano in this zone in the future cannot be ruled out, and these areas should be designated as "unfavorable areas" (orange) for geological disposal. Additionally, groundwater poses a significant challenge for geological disposal, as it can transport radionuclides to the surface and contaminate the environment. However, the Nationwide Map fails to consider groundwater as an independent requirement, and the criteria used to develop the map do not account for other factors that may impact the suitability of geological disposal, such as the type of rock strata, geological structure, sea-level rise, large area volcanic ash deposits, or coastal topography [34].

Moreover, some experts argue that geological disposal is not feasible in Japan. According to Doi [65], the number of known faults in the Japanese archipelago is extremely limited, and there may be several tens of more faults. The large volume of groundwater in many areas may also pose a challenge to HLW disposal, as even normally impermeable rocks such as volcanic rocks can have numerous cracks and dense masses that could allow radionuclides to leach into groundwater and diffuse underground over tens of thousands of years. Furthermore, Japan's location in a zone of crustal movement means that it is difficult to guarantee the long-term stability of the lithosphere around the disposal site. Funabashi [71] similarly reported that the Science Council of Japan's review committee for the 2012 Responses had concluded that "for the present, there is no specific shared view among natural scientists regarding a 100,000-year stable stratum in Japan that would enable safe geological disposal" (p. 90).

Nishikawa, Takahashi, and Saito [72] highlight that information on social features such as population size and industrial location is completely excluded from the Nationwide Map. They argue that locating a geological disposal facility in an urban area is unrealistic, given the enormous costs associated with land acquisition, consensus-building by many stakeholders, and the risk of accidents; it is practically impossible to consider geological disposal sites by ignoring these social characteristics.

In anticipation of such criticism, the Waste GW claimed in its 2016 document, *Handling of Social Scientific Viewpoints Related to the Presentation of Scientifically Promising Sites*, that it had avoided setting requirements and standards from a social scientific point of view for two reasons. First, the public had not sufficiently gained an understanding of the safety and technical reliability of geological disposal through dialogical activities conducted by the NUMO throughout the country. Therefore, it was necessary to prevent the public's misunderstanding that safety assurance might be undervalued by starting discussions on disposal site selection from a different perspective. Second, there is a public view that urban areas should not be excluded from candidate sites for disposal site selection based on criteria such as population density. Instead, such areas should confront this issue as their problem because they are the major consumer areas of utility services [73].

The original policy aimed to present scientifically promising sites from both earth science and social science perspectives. However, the Waste WG decided that it was appropriate for the NUMO, the official implementing agency, to conduct studies from a social scientific perspective at the latest opportunity during the literature survey stage, thereby relinquishing their social scientific commitments [73]. Experts in the field are well aware of the NUMO's lack of social science expertise, and some may consider this a waiver of responsibility as professionals, since the Waste WG, a committee of experts, allows presenting scientifically promising sites only from the perspective of earth science, leaving social scientific appraisal in the hands of an implementing agency [24]. In an effort to facilitate public acceptance, the Waste WG presented only the natural scientific standpoint of standards and criteria, thereby focusing solely on the safety aspect. This approach reflects a bias toward natural scientific viewpoints and reveals a social construction of scientific knowledge aimed at easing public acceptance of geological repositories.

In the context of the official concept of "the government taking the lead" in HLW disposal, the original intent of the Scientific Council was for the government to establish a democratic platform for risk communication between a third-party scientist group (including social scientists) and lay people. However, the government's implementation of this concept has taken a different form, where the parastatal apparatus such as the NUMO engages directly with citizens in a unilateral, persuasive manner. For instance, the NUMO's material for national briefing sessions stated, "Using this map, we would like to deepen your interest and understanding by sharing the prospect that underground environments with favorable characteristics for geological disposal exist widely in Japan" [74] (p. 7). According to Sato and Tayusho [75], who attended the briefing sessions held in Osaka and Kobe in 2018, the NUMO officers stated that the final disposal site could be selected with the understanding of citizens and could be constructed anywhere except in the immediate vicinity of volcanoes and active faults. However, the government did not set conditions or standards that are more rigorous in terms of natural science and more realistic in terms of social science, perhaps because doing so might have limited the range of social acceptance and made it more challenging to identify candidate sites. The NUMO organizers' primary concern appeared to be the political and administrative goals of geological siting, with long-term safety considerations being secondary. Consequently, any area shown in green on the Nationwide Map was deemed acceptable, and any citizen participating in the briefing session was encouraged to consider accepting the disposal site. This renunciation of scientific rigor by professional scientists and the implementation agency could negatively impact the social acceptance of HLW disposal siting, as it may create a perception of insufficient scientific integrity and an inadequate level of attention being given to citizens' concerns through bilateral and democratic deliberation processes. The risk communication approach adopted by the NUMO is considered too conservative and fails to address participants' concerns regarding interpersonal fairness.

The case of Toyo Town illustrates the impasse of conventional policy approaches to securing local social acceptance for repository siting in two critical respects. First, the use of monetary incentives, which has been a cornerstone of Japan's nuclear policy, is less applicable to geological disposal. While the provision of subsidies under the Three Laws for Power Development has been a central measure to address the inequitable distribution of benefits and costs resulting from the siting of nuclear power plants, studies suggest that such incentives have limited efficacy in fostering social acceptance of geological disposal [76,77]. Fray et al.'s [78] case study in Switzerland further supports this view, finding that respondents were more likely to accept a disposal site without financial compensation, and that the offer of such compensation was perceived as a form of bribery and met with opposition. This echoes the criticism leveled by Governor Hashimoto of the Kochi Prefecture, who decried Japan's geological disposal policy as "slapping the cheek with a wad of banknotes" [40] (p. 38).

The second issue is the lack of trust among local residents regarding the procedural fairness of the location process. In Toyo Town, Mayor Tashima submitted the survey application as a local mayor had the veto right at each stage of the geological survey of a potential repository site. Opponents developed their opposition campaign, citing that "once an applicant has applied for a literature survey, there is no going back" [40] (p. 31). This may have been a resistance strategy employed by the opposition activists. However, the fact that local residents questioned the possibility of exercising their "veto power" suggests that they lacked sufficient trust in the official selection process for the disposal site. The historical fact behind this is that the official process for locating a nuclear power plant in the past was often regarded as a mere formality that depended on informal negotiations between the electric power companies and the candidate sites. Additionally, there was a public distrust of the "democratic procedure" of the Diet, which passed the Final Disposal Law in just two and a half months without adequate debate in the Diet or sufficient media coverage at the national level [40].

The recent applications for the literature survey and subsequent survey process made by Suttsu Town and Kamoenai Village have suggested that the use of financial compensation measures could facilitate the social acceptance of HLW repository siting. However, the intentions behind Suttsu Town's application show that this strategy may not be a reliable long-term solution. Although monetary benefits could initially sway public opinion in favor of HLW repository siting, the mayor emphasized the importance of maintaining veto rights throughout the selection process and proposed a local referendum to decide whether to proceed with the geological survey. This suggests that financial compensation may not guarantee long-term social acceptance. The mentality of "let's get money and go away" is likely to occur when there is little evidence of local people's trust in the safety of repository siting and when there are no other incentives or considerations for intergenerational equity other than monetary compensation. This type of subpolitics, if it exists, will ultimately be counterproductive to the government's long-term goals. Relying on temporary financial provisions without a long-term plan to support the socioeconomic and cultural backbone of the host community will result in a distorted fulfillment of distributive fairness, leading to more risks than benefits over time.

The discussions between the NUMO and the local resident representatives of Suttsu Town and Kamoenai Village, held in parallel with the literature review, occur once a month or two months, and the resident committee members are free to ask questions or submit requests to NUMO officers. At a symposium held in Kamoenai Village in May 2022, Mr. Ban Hideaki, a co-representative of the Citizens' Nuclear Information Center, an advocacy group critical of Japan's nuclear policy, was invited to speak. Mr. Ban provided information to villagers from a critical viewpoint of Japan's reprocessing and HLW geological disposal policy. Some may view the NUMO's dialogue with residents as a form of unilateral propagation by the government [53]. However, the agency's efforts to ensure a degree of deliberative democracy by allowing increased knowledge among residents through recurrent meetings and information provision from a citizen group critical of Japan's nuclear power policy, which may be disadvantageous to the NUMO, are commendable. Nonetheless, participation in each meeting was limited to a small number of residents who were committee members. Since the Science Council of Japan advocates a two-way communication approach where experts, who take a neutral position from the government, engage in dialogue with citizens, the NUMO appears to maintain the same communication issues as the briefing sessions held nationwide.

Two contrasting cases in the United States offer insights for achieving smooth and equitable public acceptance of HLW geological repositories in Japan. The Waste Isolation Pilot Plant (WIPP) in New Mexico is a successful deep geological repository of radioactive waste. It is the only facility in the US that has achieved permanent disposal of such waste, including specific types of TRU waste generated during the Cold War era for US nuclear weapon manufacturing. This radioactive waste is stored approximately 2000 feet underground beneath the New Mexico desert, and spent nuclear fuel from nuclear power plants is not involved [79]. According to Jenkins-Smith et al. [80], state officials consider defense-related waste more acceptable than HLWs because the former is perceived to be less hazardous. Since the New Mexico Environment Department (NMED) approved the issuance of a Hazardous Waste Facility Permit to the US Department of Energy (DOE) for the storage and disposal of TRU waste in 1999, over 90,000 cubic meters of waste have been transported to and disposed of at the WIPP through 12,000 shipments [81].

According to research on the WIPP case, residents living near the WIPP facility and transportation route were more supportive of it, whereas support decreased as the distance from the facility increased. This may be due to various factors, including expectations of economic benefits and safety assurances [80]. The WIPP conducted an extensive outreach program that included numerous meetings with the public and the training of potential emergency responders among residents. These efforts helped build trust and confidence between the WIPP and local communities, leading to increased support [82]. Increased familiarity with people and technology, together with state funding support for road improvements, significantly influenced local support for the WIPP [80]. Although there are differences between the WIPP case and the siting of an HLW repository in Japan (e.g., differing radioactive risks between TRU waste and HLWs), this experience provides insight into the future needs and challenges for safety assurance in candidate repository sites in Hokkaido, where there has been little cooperation between the prefecture and the local area.

Yucca Mountain in Nevada is another example from the United States. In 1987, Congress selected Yucca Mountain as a potential site for the disposal of spent nuclear fuel and HLWs. By the early 1980s, salt domes and reprocessing were no longer viable options and a large-scale deep geological repository was necessary to handle the growing stockpiles of domestic spent nuclear fuel. The National Waste Policy Act of 1982 directed the DOE to establish one facility each in the west and east. However, strong opposition from eastern states with many congressional delegates led to the decision to place the repository only in the relatively less populated and vast western regions. The DOE announced three potential sites in Texas, Washington, and Nevada in 1986; however, only Yucca Mountain received legislation for intensive study, which was passed in December 1987, as Nevada had the smallest congressional delegation. In 1989, Nevada passed legislation that made the acceptance of HLWs within the state illegal and refused to grant environmental permits for investigations at Yucca Mountain. In 2009, President Barack Obama ended support for repository development at Yucca Mountain, and it was no longer a candidate site. Over the 20 years until then, Nevada and the federal government had engaged in a series of political battles, including scientific controversies over the likelihood of earthquakes, volcanic eruptions, and underground radioactive water contamination in the area surrounding Yucca Mountain. The government spent nearly $10 billion on this issue [83].

Japan and the United States have different governance systems, but a common structure is that the only repository for spent nuclear fuel in the country must accept all HLWs, and provincial stakeholders fiercely oppose this acceptance. In the United States the host state receives $20 million per year (initially it was set at $100 million), but in Japan most of the compensation goes to host communities, with less distribution to prefectures. Japan can learn from the Yucca Mountain case that, despite spending large sums of money, repository acceptance may fail because of opposition from the sole province forced to accept it. The opportunity cost of discontinuation increases as local investigations advance. The Japanese government must engage in active dialogue not only with the residents of the host communities but also with the Hokkaido government.

In conclusion, a significant obstacle to achieving social acceptance of Japan's repository siting is the lack of fundamental restructuring of the current nuclear power policy that lost public credibility because of the Fukushima Daiichi nuclear power plant accident. The government is pursuing the repository siting process separately without taking into account the uncertainties and ambiguities that the current level of natural scientific knowledge and wisdom cannot resolve. By insisting on scientifically assured safety and inducing monetary merits, the government is unlikely to gain public trust for the eventual acceptance of an HLW repository site.

It is noteworthy that the government and scientists under its thumb are attempting to advance nuclear power policy and repository siting within the conventional paradigm of the first modernity. The current Kishida administration regards nuclear power as "clean energy" from the perspective of decarbonization for global warming mitigation. This expresses the premise that nuclear power generation can be entirely regulated by science, and sustainable development can be accomplished while minimizing its negative environmental impact through the rational use of science and technology.

The Japanese government's convictions and adherence to conventional nuclear power policies are grounded in several political and economic factors that intersect in various ways. One such factor is the entrenched nuclear village (*genshiryoku mura*) that is firmly embedded in Japanese society. This close-knit network of individuals and organizations involved in the nuclear industry, including utility companies, politicians, government officials, nuclear experts, and the prefectures and communities where nuclear facilities are located, has a significant influence on the perpetuation and expansion of conventional nuclear power policies. Second, the government's confidence in the safety and public acceptance of nuclear power strengthened after it bolstered the safety regulations for existing nuclear power plants following the Fukushima Daiichi nuclear disaster. Third, the closure of nuclear power plants due to the disaster resulted in greater reliance on fossil fuels, which was further exacerbated by the outbreak of the Russia–Ukraine crisis in February 2022, causing energy costs to escalate. In addition to these factors, some attribute the persistent need for nuclear power in Japan to the geographical, economic, and technical limitations of renewable energy sources such as solar and wind. However, it is conceivable to view the situation in reverse, given that the Liberal Democratic Party and successive cabinets, who were eager to revive nuclear power after the Fukushima disaster, restricted investments in renewable energy.

While the German government decided to abandon its nuclear power policy in the wake of the Fukushima Daiichi nuclear disaster and recently achieved a nuclear phase-out amidst the Russia–Ukraine crisis, the Japanese government, which held power at the time of the accident, is striving to restore its nuclear power system more vigorously. This underscores the significant depth of the structural lock-ins and their shortcomings, including the government's political will. A crucial step in changing the decade-long stalemate is the active engagement of social movements from civil society in dialogue with influential politicians and other key stakeholders in the nuclear industry.

The policy side's adherence to the first modernity notwithstanding, the foregone analysis illuminates that the actual contemporary circumstances of the science and technology of nuclear power utilization and its public awareness in the country are already within the domain of a risk society, demanding a reflexive response from the policy side. The government and scientists should recognize the fundamental need for acknowledging and accepting the actual magnitude of risks associated with prevailing scientific uncertainties and ambiguities, hence, exploring sustainability from a reflexive perspective of how to face and live with them.

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Appendix A

Table A1. The twelve recommendations included in the 2015 Recommendations document.

(1) Temporary storage method and period **Recommendation 1.** Regarding the temporary storage method for both vitrified waste and spent fuel, ground storage is recommended from both safety and economic standpoints, using technologies such as dry (air-cooled) casks (container) or vaults (pit) with sealing and shielding functions.
Recommendation 2. In principle, the period of temporary storage is 50 years, during which consensus will be reached for geological disposal, a suitable site and candidate site will be selected, and a disposal site will be constructed within 20 years of reaching the consensus, leaving a 30-year period for this purpose. In case of unforeseen circumstances, such as natural disasters, an extension may be possible.
(2) Equity of business operators' responsibility and inter-regional burden **Recommendation 3.** Regarding the storage and disposal of high-level radioactive waste, responsibility should lie with the business operators who generated them. Additionally, the public must acknowledge their role as beneficiaries of nuclear power generation, whether by choice or not, and actively engage in the formation of public opinion on the selection and construction of temporary storage facilities and final disposal sites.
Recommendation 4. It is desirable that the temporary storage facility be located in at least one location within the power distribution area of the utility company that owns the nuclear power plant. The company should select the location and construct it at its own responsibility. Additionally, to ensure fairness of burden, it is desirable to construct this facility at a site separate from the nuclear power plant.
Recommendation 5. In selecting candidate locations for temporary storage or final disposal, and constructing and managing facilities, we fully consider the intentions of the candidate locations and the areas that involve them (i.e., diverse local governments such as townships, municipalities, and prefectures).
(3) Responsible behavior for future generations **Recommendation 6.** We should sincerely reflect on the responsibility of the current generation, which has chosen to engage in the irreversible act of producing high-level radioactive waste from nuclear power generation, with regard to future generations. Along with ensuring the safety of temporary storage, we should not unduly procrastinate its duration.
Recommendation 7. Decisions regarding the issue of restarting nuclear power plants should be based on ensuring safety, obtaining the consent of the local community, and securing storage capacity for newly generated high-level radioactive wastes while creating plans for temporary storage. Resuming operations without concrete plans for temporary storage would be irresponsible towards future generations.

Table A1. *Cont.*

(4) Candidate sites for final disposal and risk assessment **Recommendation 8.** Regarding the selection of suitable sites for final disposal, it is necessary to examine the current geological knowledge and create a list of potential sites for the entire country. In addition, when selecting candidate sites, it is important to prioritize the voluntary acceptance of local governments in the relevant areas rather than relying solely on proposals from the national government. The responsibility for listing suitable sites falls on the *Expert Investigation Committee on Scientific and Technological Issues* (provisional name), which will be discussed further.
Recommendation 9. Important issues to be addressed during the temporary storage period include the risk assessment of geological disposal and the implementation of risk mitigation measures. The safety of geological disposal needs to be thoroughly discussed by various experts who hold different views on nuclear power generation. The *Expert Investigative Committee for Scientific and Technological Issues* is responsible for coordinating these issues.
(5) Organizational structure for consensus-building **Recommendation 10.** To address the issue of high-level radioactive waste based on social consensus, a *Committee for Comprehensive Policy on High-Level Radioactive Waste* (provisional name) should be established to formulate policies that reflect public opinions. This committee will supervise the *National Council on Nuclear Waste Issues* (provisional name) and the *Expert Investigation Committee on Scientific and Technological Issues*, which will be discussed later. The committee members should be selected in a manner that is open to interested parties in various positions, but its core members should be individuals with no interest in promoting the nuclear power business.
Recommendation 11. The devastating accident at the Fukushima Daiichi nuclear power plant and the subsequent process of dealing with it have made the public increasingly distrustful of the scientific community, utility companies, and the government. As a result, the public's trust in those involved in nuclear power generation has been severely damaged. Restoring this trust is particularly important in solving the high-level radioactive waste disposal problem. To achieve this, a *National Conference on Nuclear Waste Issues* should be established with a focus on public participation.
Recommendation 12. An *Expert Investigation Committee on Scientific and Technological Issues* should be established as an advisory body to conduct thorough investigations and research on scientific and technological issues concerning the safety of temporary storage and geological disposal facilities and their management. When establishing this committee, we should adopt the principles of confirming the interests of experts, a public recommendation system, and public support to secure autonomy, independence, fairness, and neutrality, and obtain social credibility.

Source: [56].

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