

Risk Governance and Stakeholder Analysis of Radioactive Waste Management in Small Modular Reactor Deployment: Evidence from Thailand[†]

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Abstract

Background and Objectives: Thailand is currently considering the integration of Small Modular Reactor (SMR) technology into its national energy portfolio under the Power Development Plan (PDP 2025–2037) as part of its transition toward low-carbon energy and climate commitments. As a newcomer nuclear country without upstream fuel-cycle capabilities—such as uranium mining, enrichment, or fuel fabrication—Thailand operates as a back-end nuclear system, where the primary responsibility lies in managing spent fuel and radioactive waste. This creates significant challenges across technical, financial, regulatory, and social dimensions, particularly given the absence of established infrastructure and institutional arrangements for long-term waste management. Against this backdrop, a systematic understanding of risks associated with the SMR back-end cycle is essential to ensure that nuclear adoption is economically viable, environmentally sustainable, and socially acceptable. This study therefore aims to (1) identify key stakeholders across four stages of the SMR back-end cycle—waste generation, interim storage, transportation, and final disposal—and (2) evaluate the associated risk factors using a structured risk-governance framework.

Methodology: The study applies a qualitative risk-governance framework grounded in ISO 31000:2018 and IEC/ISO 31010:2019 standards, complemented by relevant International Atomic Energy Agency (IAEA) Safety Standards. The analytical process follows four steps: context establishment, risk identification, risk analysis, and risk evaluation. Risk identification is conducted across the four stages of the SMR back-end cycle, yielding 21 risks classified into four dimensions: technical, financial, policy/regulatory, and social/environmental. A qualitative likelihood–consequence matrix—combining four likelihood levels (L1–L4) and five consequence levels (C1–C5)—is employed to categorize risks into low, medium, high, and extreme levels, thereby enabling a systematic assessment of both probability and impact across the waste management lifecycle.

Key Findings: The results show that the overall risk profile of Thailand’s SMR back-end cycle is driven primarily by non-technical factors, despite the presence of advanced engineering safety features. Technical risks are generally assessed as low to medium,

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reflecting the reliability of passive safety systems and established international standards governing radioactive material management. In contrast, financial, regulatory, and social risks emerge as the principal constraints. Financial risks are assessed as high, particularly those associated with long-term storage, maintenance, and repository development, due to their persistent and intergenerational cost burden in the absence of a dedicated national funding mechanism. Policy and regulatory risks are predominantly medium, reflecting uncertainties in SMR integration into national energy planning, licensing processes, and the absence of a clearly defined long-term disposal strategy, indicating fragmented institutional arrangements. Social risks constitute the most critical challenge, with community opposition identified as the only “extreme” risk, driven by concerns over radiation safety, limited institutional trust, and potential conflicts in stakeholder engagement, all of which affect the social license to operate.

Policy Implications: The findings suggest that the successful deployment of SMR technology in Thailand depends more on strengthening governance and institutional capacity than on addressing technical constraints alone. First, establishing a long-term financing mechanism—such as a national radioactive waste management fund—is essential to ensure fiscal sustainability, with a hybrid model combining short-term cost recovery, operator contributions, and long-term statutory funding recommended to address intergenerational liabilities. Second, improving regulatory coherence and institutional coordination is critical to reducing policy uncertainty, including clarifying agency roles, streamlining licensing procedures, and establishing a centralized coordination mechanism for radioactive waste management, alongside early investment in interim storage and final disposal planning. Third, enhancing public trust through transparent communication, continuous stakeholder engagement, and environmental monitoring is vital, with nuclear literacy programs and participatory frameworks aligned with international best practices playing a key supporting role. Overall, strengthening financial, institutional, and social foundations will be crucial to ensuring that SMR adoption contributes effectively to Thailand’s long-term energy transition.

Keywords: Small Modular Reactor (SMR); Radioactive Waste Management; Nuclear Waste Risk Assessment; Stakeholder Analysis; Energy Policy and Public Acceptance

JEL Classification Codes: Q48; Q53; H87; D81

1. Introduction

Thailand’s pursuit of sustainable energy has entered a critical phase, as rising electricity demand and declining fossil-fuel resources coincide with strengthened national climate commitments under the updated Power Development Plan (PDP 2025) and the Nationally Determined Contribution (NDC 3.0). These targets aim to reduce greenhouse gas emissions by 47% by 2035 (relative to 2019 levels) and achieve net-zero emissions by 2050. Together, these challenges necessitate a strategic diversification of the country’s energy portfolio and accelerated investment in low-carbon and alternative energy sources, including solar, biomass, wind, hydropower, and emerging nuclear technologies—particularly Small Modular Reactors (SMRs)—as part of long-term decarbonization efforts.

The regional energy landscape in Southeast Asia reflects a similar transition. Countries such as Indonesia, Malaysia, and the Philippines have initiated preparatory frameworks and exploratory efforts toward nuclear power as part of their long-term strategies to diversify energy mixes and support decarbonization. These developments

signal that nuclear energy is increasingly recognized as a viable complement to renewable sources in achieving energy security and sustainability goals (World Nuclear Association [WNA], 2025). Collectively, these regional trends underscore the re-emergence of nuclear energy as a strategic component of sustainable energy transitions, particularly in economies seeking to balance carbon reduction with energy security. For Thailand, the potential integration of nuclear energy into the PDP 2025 aligns with these global and regional directions toward a low-carbon and resilient energy system. In this context, understanding the risks and governance mechanisms associated with spent fuel and radioactive waste management is essential to ensure that future SMR deployment supports both environmental sustainability and economic policy efficiency.

Under Thailand's Power Development Plan (PDP 2025–2037), the Ministry of Energy has identified SMRs as a potential addition to the national power mix, including a proposed pilot project of approximately 300 megawatts (MWe) to enhance grid reliability and reduce dependence on natural gas (Energy Regulatory Commission, 2025; Ghoshal & Setboonsarng, 2024; International Atomic Energy Agency [IAEA], 2025a). SMRs offer several advantages, including modular scalability, enhanced safety features, and smaller land requirements, making them suitable for both industrial applications and remote areas. However, beyond electricity generation, the adoption of SMR technology presents significant challenges related to spent-fuel and radioactive-waste management—issues that are critical for long-term environmental sustainability and public acceptance.

Accordingly, this study aims to: (1) identify the stakeholders involved in spent-fuel and radioactive-waste management across the key stages of the SMR fuel cycle—generation, interim storage, transportation, and final disposal; and (2) examine the key risk factors across four dimensions: technical, financial, policy, and social.

This study contributes to the applied economics literature by conceptualizing radioactive waste management as a long-term fiscal and institutional challenge. In particular, it highlights issues related to intergenerational cost allocation, public financing mechanisms, and governance risks within the broader context of energy transition policy.

The remainder of the paper is organized as follows. Section 2 presents the literature review. Section 3 describes the methodology. Section 4 discusses the empirical results. Section 5 concludes, and Section 6 provides policy implications.

2. Literature Review

2.1 Current Status on Nuclear Power Plant in Thailand

Thailand has not yet operated any commercial nuclear power plants; its sole facility is the TRR-1/M1 research reactor under the Thailand Institute of Nuclear Technology (TINT), used for research and education (IAEA, 2025a). The PDP 2025 considers integrating SMR technology with a total capacity of roughly 600 MW (2×300 MW) as part of the national low-carbon strategy (Energy Regulatory Commission, 2025; Ghoshal & Setboonsarng, 2024).

The IAEA Milestones Approach outlines 19 infrastructure issues for newcomer countries embarking on nuclear programs, covering legal and regulatory frameworks, nuclear safety, radioactive-waste management, human-resource development, and stakeholder engagement. Thailand has participated in the INIR (Integrated Nuclear Infrastructure Review) and ARTEMIS (Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation) missions to assess its readiness (IAEA, 2022, 2024).

Within the nuclear fuel cycle, Thailand is considered a back-end nation because it has no domestic uranium mining, enrichment, or fuel-fabrication facilities. Therefore, domestic waste arises solely from downstream processes—spent-fuel storage, transport, and disposal—which must adhere to IAEA and Nuclear Energy Agency (IAEA, 2025c) standards to ensure long-term safety.

2.2 Comparative Models of Back-End Nuclear Waste Management in Asia

Asian nuclear programs have adopted different financing and governance mechanisms for spent fuel and radioactive-waste management, reflecting varying levels of technological maturity, regulatory capacity, and institutional readiness. Three policy approaches are particularly relevant to Thailand's emerging SMR pathway: fund-based, polluter-pays, and fee-for-service models (IAEA, 2022; IAEA, 2025c).

Korea represents the most advanced institutional case. Under the Radioactive Waste Management Act (RWMA), nuclear operators pay levies based on electricity generation and spent-fuel inventory into a statutory Radioactive Waste Management Fund administered by the Korea Radioactive Waste Agency (KORAD). The legislative framework was strengthened in 2021–2025 through the proposed High-Level Radioactive Waste Management Act, which establishes legally binding milestones for interim storage by 2050 and final disposal by 2060 (IAEA, 2025b; IAEA, 2025c). This model demonstrates how long-term nuclear liabilities can be internalized through earmarked levies and intergenerational capital reserves, reducing sovereign exposure and improving public confidence. Indonesia, currently in the pre-deployment stage, uses a polluter-pays model defined in the National Policy and Strategy for Radioactive Waste and Spent Fuel (Jakstranas 2018–2045) (Bapeten, 2025). Under this scheme, waste generators finance treatment and interim storage services provided by the Radioactive Waste Technology Center (PTLR) under the National Research and Innovation Agency (BRIN), while BAPETEN oversees regulatory compliance. The policy is intended to evolve into a dedicated national fund following future reactor deployment, acknowledging both institutional limitations and phased development typical of newcomer nuclear states; Forum for Nuclear Cooperation in Asia (FNCA, 2023, IAEA, 2024). This approach reflects a risk-sharing model appropriate to countries transitioning from research reactors to commercial nuclear power. Malaysia, despite not yet operating any power reactors, provides a third example through its fee-for-service and regulator cost-recovery mechanism. Under the Atomic Energy Licensing Act 1984 (Act 304), the Atomic Energy Licensing Board (AELB) collects licensing and regulatory fees, while Nuclear Malaysia provides chargeable radioactive-waste treatment, conditioning, and interim storage services for medical, industrial, and research users (Abdul Latif et al., 2021, Department of Atomic Energy Malaysia, 2023). Although not yet applied to high-level waste, this system illustrates how regulatory cost recovery and predisposal infrastructure can be developed before nuclear power deployment, consistent with IAEA Milestones Phase 1–2 requirements.

Taken together, these cases illustrate the policy choices available to Thailand: Korea's fund-based model ensures long-term fiscal certainty, Indonesia's polluter-pays system offers flexibility for staged development, and Malaysia's fee-based approach demonstrates early institutional capacity-building without full reactor commitment. These models provide relevant pathways for Thailand's SMR program to design sustainable financing mechanisms, strengthen regulatory accountability, and sequence waste-infrastructure development in alignment with IAEA safety standards and Milestones (IAEA, 2018b; IAEA, 2025c).

2.3 Approaches to Risk Assessment in Nuclear Waste Management

Risk assessment methodologies for nuclear-waste governance range from qualitative frameworks to highly quantitative models. Among the most commonly used tools in early-stage nuclear planning is the risk matrix, a qualitative technique recommended under ISO 31000 (International Organization for Standardization [ISO], 2018) framework together with IEC/ISO31010 (International Electrotechnical Commission & International Organization for Standardization [IEC/ISO], 2019) widely applied in IAEA and OECD NEA guidance for risk-informed decision making in newcomer nuclear countries (IAEA, 2020b; Nuclear Energy Agency [NEA], 2019). Risk matrices are frequently used in nuclear waste and energy-infrastructure studies because they allow risks to be evaluated and communicated based on likelihood and consequence even in the absence of detailed operational data. For this reason, risk matrices are often adopted in early SMR and radioactive-waste governance research where uncertainties remain high and stakeholder participation is essential (Witt & Ramzan, 2017; Xiao et al., 2024).

Beyond risk matrices, the literature documents a variety of alternative or complementary methods. Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP) have been applied to nuclear-waste siting and policy prioritization to incorporate stakeholder value judgments and weighted factors (Schwenk-Ferrero & Andrianov, 2017; Wang et al., 2023). Fuzzy logic and Bayesian probabilistic models are used when uncertainty is high and empirical failure-rate data are limited (Singh et al., 2022; Suh et al., 2021;). Engineering-based risk techniques such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Bow-Tie analysis remain central in reactor safety and accident progression studies, whereas Delphi methods and stakeholder salience frameworks are used to assess governance and social acceptance dimensions (Hietala & Geysmans, 2022; Hoti et al., 2021; Perko et al., 2025).

However, the application of highly quantitative tools is often infeasible in early-phase nuclear programs where site-specific or operational data do not yet exist. In line with IAEA infrastructure-development recommendations for newcomer countries, qualitative risk matrices paired with structured stakeholder analysis are considered suitable for preliminary planning, policy design, and risk prioritization. Therefore, based on the methodological landscape and Thailand's current SMR readiness level, this study adopts the ISO 31000 qualitative risk matrix as the primary analytical tool, complemented by stakeholder mapping to capture institutional and socio-political dimensions.

3. Methodology

3.1 Overall Approach and Risk-Governance Framework

This study adopts a structured risk-governance framework based on ISO 31000:2018 and IEC/ISO 31010:2019 to identify, analyze, and evaluate risks associated with spent-fuel and nuclear-waste management in Thailand's prospective SMR program. The framework provides a systematic basis for policy evaluation under uncertainty, allowing for comparison of risk exposure across institutional and economic dimensions. The methodology reflects a full-cycle perspective—covering generation, interim storage, transportation, and final disposal—and integrates nuclear-sector-specific requirements from the IAEA Safety Standards, particularly GSR Part 5 (Predisposal Management of Radioactive Waste), SSR-5 (Disposal of Radioactive Waste), and SSR-6 (Transport of Radioactive Material). The analytical process follows

ISO 31000's structured steps: context establishment (including SMR characteristics, national policy environment, and back-end obligations), risk identification, risk analysis, risk evaluation, and risk treatment recommendations.

The analysis employs a qualitative risk matrix using four levels of likelihood (L1–L4) and five levels of consequence (C1–C5). This matrix is used to classify each identified risk into four categories: low, medium, high, and extreme.

3.2 Risk Identification Across the Nuclear Fuel Cycle

Risk identification was conducted for each stage of the SMR back-end cycle: waste generation, interim storage, transportation, and long-term disposal. Risk sources were categorized into four dimensions: technical (e.g., cooling failures, transportation accidents), financial (e.g., maintenance and long-term storage costs), policy and regulatory (e.g., PDP alignment and licensing delays), and social and environmental (e.g., public acceptance and participation conflicts).

3.3 Stakeholder Analysis Methodology

The stakeholder analysis follows a structured approach informed by the IAEA Milestones framework, particularly Issues 2 (regulatory framework), 12 (radioactive-waste management), and 17 (stakeholder involvement). A multi-step process was applied. First, stakeholders were identified and classified into four groups: (1) policy and regulatory bodies—such as the Ministry of Energy (MOE), Office of Atoms for Peace (OAP), Energy Regulatory Commission (ERC), Office of Natural Resources and Environmental Policy and Planning (ONEP), and Ministry of Natural Resources and Environment (MNRE); (2) operators and technical organizations—including the future SMR operator, Thai Industrial Standards Institute (TISI), and emergency-response agencies; (3) social and environmental stakeholders—such as local communities, civil society, and academia; and (4) international organizations, including the IAEA, ASEAN/ASEANTOM, and international vendors. This classification is consistent with approaches used in nuclear governance and waste-siting studies (Aaltonen et al., 2015; Cotton, 2012; Di Nucci et al., 2015).

Second, stakeholder mapping and influence analysis were conducted using a modified power–interest matrix to assess each actor's potential influence on SMR back-end decisions. Power was evaluated based on formal authority, regulatory jurisdiction, and operational control, while interest was assessed in terms of expected impacts, responsibilities, and socio-political sensitivity. Finally, stakeholders were systematically linked to the identified risk factors to highlight their roles in shaping risk emergence and management.

3.4 Risk Analysis and Risk Matrix Application

Following risk identification, each risk was assigned a likelihood (L1–L4) and consequence (C1–C5) rating based on multiple sources of evidence, including international nuclear safety performance statistics (e.g., spent-fuel pool failure probabilities below 10^{-6} per year and transport accident rates below 10^{-6} per shipment), socio-political evidence (such as public surveys, EHIA case studies, and historical nuclear opposition), financial benchmarks from OECD NEA and IAEA (including operation and maintenance costs and long-term storage expenditures), and Thailand's policy timeline (e.g., the anticipated need for final disposal after 2070). A consolidated risk matrix (Figure 1) was then applied to determine the overall classification of each risk as low, medium, high, or extreme.

C5	M	H	E	E
C4	M	M	H	E
C3	L	M	M	H
C2	L	L	M	M
C1	L	L	L	M
	L1	L2	L3	L4

Figure 1. Risk Matrix

Source: Adapted from International Electrotechnical Commission and International Organization for Standardization (2019) and International Organization for Standardization. (2018).

As Thailand does not yet operate SMRs or commercial nuclear-waste facilities, the analysis relies on expert-based assessment, regulatory review, and international comparison rather than site-specific operational data. ISO 31000 and IAEA guidelines recognize such expert-based approaches as appropriate for preliminary risk assessment in early-stage nuclear programs, where empirical data are limited but policy decisions are required.

4. Results and Discussion

Because stakeholder responsibilities and influence patterns shape the emergence and severity of risks in Thailand's SMR back-end cycle, this section begins by outlining the key stakeholder landscape, followed by an analysis of the associated technical, financial, policy, and social risks.

4.1 Key Stakeholders in Thailand

In accordance with Thai legislation and IAEA guidelines, the implementation of an SMR project requires coordinated participation from multiple institutions across policy, operational, social-environmental, and international levels.

At the policy and regulatory level, the Ministry of Higher Education, Science, Research and Innovation (MHESI) oversees nuclear science policy and coordinates with the IAEA under the National Science, Technology, and Innovation Act. The Office of Atoms for Peace (OAP) serves as Thailand's national nuclear safety and regulatory authority under the Peaceful Uses of Atomic Energy Act B.E. 2559 (2016), which establishes the legal framework for nuclear and radiological safety, licensing, and regulatory oversight. The Ministry of Energy, together with the Energy Policy and Planning Office (EPPO), is responsible for formulating the national Power Development Plan (PDP). Meanwhile, the Energy Regulatory Commission (ERC) regulates the electricity sector, including tariff setting, licensing oversight, and the governance of sectoral financial mechanisms such as decommissioning funds, in coordination with relevant agencies. The Thailand Institute of Nuclear Technology (TINT) plays a key role in nuclear research and radioactive-waste storage.

At the operational and technical level, SMR operators—such as the Electricity Generating Authority of Thailand (EGAT) or licensed private entities—will be responsible for reactor operation and spent-fuel management in compliance with IAEA

safety standards. Universities and research institutions contribute to human-resource development and research and development (R&D), supporting the long-term capacity of the nuclear sector. In addition, local communities surrounding potential project sites play a critical role in establishing a social license to operate (SLO).

At the social, environmental, and public-safety level, the Office of Natural Resources and Environmental Policy and Planning (ONEP) is responsible for the review and approval of Environmental and Health Impact Assessments (EHIA). The Pollution Control Department (PCD) supervises hazardous-waste transport and disposal, while the Department of Disaster Prevention and Mitigation (DDPM) coordinates preparedness and response for radiological and nuclear emergencies. Public participation—particularly from local communities—is formally required under Thailand's EIA/EHIA regulatory framework, which mandates information disclosure, public consultation, and stakeholder hearings throughout key stages of project decision-making for activities with potential environmental and health impacts.

At the international level, the International Atomic Energy Agency (IAEA) provides safety standards and peer-review missions (e.g., INIR, IRRS, ARTEMIS), while the OECD Nuclear Energy Agency (NEA) offers technical and economic guidance, particularly in cost estimation and liability frameworks.

Overall, effective coordination across these multiple stakeholder levels is essential to ensure safe, economically viable, and socially acceptable nuclear development in Thailand.

4.2 Risk Identification

Table 1 reveals that there are 21 risks were identified. The most important issues across the SMR back-end cycle arise from the intersection of stakeholder roles and risk dimensions. At the generation stage, technical risks (GT1–GT2) relate primarily to fuel-system integrity and radiation-control performance, both of which are tightly coupled to regulatory oversight by the Office of Atoms for Peace (OAP) and operational practices of the future SMR operator. Financial pressures (GF1) emerge early due to the high cost of maintenance, surveillance, and safety inspections mandated by both IAEA and national requirements. Policy-related issues (GP1–GP2) reflect uncertainties in integrating SMR capacity into the Power Development Plan (PDP) and potential delays in licensing and EHIA approval. Social concerns (GS1–GS3) center on public fear of radiation, procedural conflict during public participation, and broader security threats—all of which influence the social license to operate.

In the interim-storage stage, risks shift toward long-term stewardship challenges. Technical issues (ST1–ST2) include cooling-system failures and natural-disaster vulnerabilities, while financial burdens (SF1) stem from multi-decade monitoring and security requirements. Policy gaps (SP1) arise from the absence of a national centralized interim-storage facility, and social concerns (SS1) relate to local opposition driven by perceived radiation risk and impacts.

During transportation, technical risks (TT1) remain low-probability but high-attention due to stringent safety standards, whereas financial pressures (TF1) reflect recurring insurance and its costs. Policy issues (TP1) relate to cross-border regulatory harmonization, and social concerns (TS1) are linked to public distrust along transport routes.

Finally, in the final-disposal stage, long-term uncertainties dominate. Technical risks (DT1) relate to Thailand's lack of a proven disposal pathway; financial risks (DF1) involve the substantial investment required for a deep geological repository and perpetual monitoring; policy gaps (DP1) stem from the absence of a national repository strategy; and social concerns (DS1) reflect the likelihood of future community

resistance once siting begins. These issues collectively illustrate that while Thailand's technical risks are generally controllable, the financial, policy, and social dimensions are far more structurally significant for long-term SMR waste-management readiness.

4.3 Risk Evaluation

The likelihood–consequence assessment (Table 2) demonstrates that the majority of risks associated with Thailand's SMR spent-fuel and nuclear-waste management fall within the medium category, with only a small number classified as high or extreme. Of the 21 identified risks, 1 is Extreme, 3 are High, 13 are Medium, and 4 are Low. The pattern reflects the structural characteristics of newcomer nuclear programs, where technical risks tend to be well controlled through international safety standards, while financial, policy, and social risks remain more pronounced.

Technical risks (e.g., GT1, ST1, TT1) are mostly evaluated as low to medium because international operating data show low failure probabilities and strong passive-safety performance for SMRs. Engineered barriers, multi-layer containment, and Type B(U) transport packages significantly limit the likelihood of severe events. However, certain technical risks—such as cooling failure in interim storage (ST1) or extreme natural events (ST2)—retain high-consequence potential, placing them in the medium category despite low likelihood. Financial risks form the largest cluster of high-priority concerns, particularly GF1 (high maintenance and inspection costs) and SF1 (long-term interim-storage costs). These recurring expenditures are certain to arise throughout the SMR lifecycle, and international benchmarks (IAEA, 2025c) show that long-term spent-fuel surveillance may require millions of dollars annually per site. Thailand's current absence of a dedicated waste fund further heightens exposure.

Policy risks (GP1, GP2, SP1, DP1) predominantly fall in the medium tier, reflecting uncertainties in PDP integration, regulatory sequencing, and long-term repository planning. Because Thailand's final-disposal strategy will not be required until after 2070, these risks are latent but material, emphasizing the need for early planning to avoid future institutional bottlenecks. Social risks constitute the most sensitive category. GS1—community opposition based on radiation fears—is the sole Extreme risk, historically demonstrated in Thailand's 2011 project suspension and consistently high public hesitation reflected in national and international surveys. GS2 (participation conflict) and SS1/TS1 (opposition to storage or transport routes) are rated High–Medium, as public consultation challenges under the EHIA system can prolong development timelines by years.

Overall, the evaluation as indicated in Table 1 shows that Thailand's SMR back-end risk profile is shaped far more by financial, governance, and social factors than by technical safety performance. Sustaining policy continuity, mobilizing long-term financing, and building social legitimacy are therefore foundational to SMR readiness.

Table 1. Risk Identification by Stage

Stage	Risk Dimension	Key Risk Factors	Principal Stakeholders
Generation / Spent Fuel Formation	Technical (GT)	GT1 – Failure of SMR fuel system -Fuel-cladding or core-design defects could cause localized overheating or loss of integrity, risking limited fission-product release despite engineered barriers (IAEA, 2018a; ISO, 2018) GT2 – Incomplete radiation control– Inadequate shielding or monitoring during operations may lead to increased occupational exposure or minor environmental release (IAEA, 2009; WNA, 2023)	OAP, TINT, SMR Operator
	Financial (GF)	GF1 – High maintenance and safety inspection costs– Frequent inspection of reactor modules and radiation-safety systems increases O&M expenses and affects cost recovery (NEA, 2019; IAEA, 2025c)	SMR Operator, ERC
	Policy (GP)	GP1 – Uncertainty of SMR integration into PDP– Delays in clarifying nuclear capacity under PDP 2025-2080 create investment hesitation (Energy Regulatory Commission, 2025; Ghoshal & Setboonsarng, 2024) GP2 – Project uncertainty during pre-construction- Licensing or EIA delays may stall project approval, extending financing risk (IAEA, 2024; ISO, 2018)	Ministry of Energy, EPPO
	Social (GS)	GS1 – Community opposition due to radiation concerns- Public fear of radiation exposure or contamination drives NIMBY resistance (IAEA, 2022; IAEA, 2025c) GS2 – Conflicts over public participation- Insufficient consultation and information transparency increase social distrust (IAEA, 2024) GS3 – Risk of terrorism or warfare- nuclear installations may face sabotage or attack risks, requiring reinforced security and emergency response (IAEA, 2018a)	Local communities, NGOs
	Technical (ST)	ST1 – Cooling-system failure- Loss of power or mechanical failure in pool/dry storage may lead to fuel overheating (IAEA, 2009) ST2 – Natural disaster damage- Earthquake or flood may compromise storage integrity and containment (IAEA, 2025c)	TINT, OAP, SMR Operator
Interim Storage	Financial (SF)	SF1 – High long-term storage and monitoring costs- Extended surveillance and security over decades raise financial burdens (Korea RWMA model, IAEA, 2025c)	SMR Operator, ERC
	Policy (SP)	SP1 – Absence of a national interim storage facility- Without centralized storage, spent fuel remains at multiple sites with fragmented responsibility (IAEA, 2022)	Ministry of Energy, OAP
	Social (SS)	SS1 – Local concern around storage sites- Fear of radiation leakage and property devaluation reduces local acceptance (IAEA, 2024; IAEA, 2025c)	Communities, NGOs
Transportation	Technical (TT)	TT1 – Accident or leakage during transport- Traffic collision or container failure could cause release of radioactive material (IAEA, 2018a)	OAP, PCD, DDPM

Stage	Risk Dimension	Key Risk Factors	Principal Stakeholders
Final Disposal	Financial (TF)	TF1 – High safety and insurance costs- Special casks, escort teams, and insurance requirements add to logistics costs (NEA, 2019)	SMR Operator
	Policy (TP)	TP1 – Ambiguity of international transport standards- Differences in cross-border regulation complicate licensing and liability management (IAEA, 2018a)	OAP, IAEA
	Social (TS)	TS1 – Public distrust along transport routes- Visible convoys and safety anxieties may provoke protests and delays (IAEA, 2022)	Communities, NGOs, Media
	Technical (DT)	DT1 – Uncertainty in long-term disposal technology (domestic or abroad) Lack of a proven repository design or international agreement creates planning gaps (IAEA, 2018a)	OAP, IAEA, TINT
	Financial (DF)	DF1 – High investment for repository construction and long-term monitoring- Repository projects require multi-billion-baht investment and perpetual oversight (IAEA, 2025c; NEA, 2019)	ERC, Ministry of Energy
	Policy (DP)	DP1 – Lack of national long-term repository strategy- Policy vacuum delays site selection and licensing (Energy Regulatory Commission, 2025; IAEA, 2022)	Ministry of Energy, ONEP
	Social (DS)	DS1 – Community resistance to repository site designation- Fear of contamination and loss of land rights triggers local rejection (IAEA, 2025c; WNA, 2023)	Communities, NGOs

Source: Authors' compilation.

Table 2. Risk Evaluation for Back-end Stage Waste Management in Thailand

Stage	Possible Risk Issue	Likelihood	Consequence	Risk	Remarks
Electricity Generation & Spent Fuel Formation	GT1. Failure of the SMR fuel system	L1	C2	L	International SMR probabilistic safety assessments report core-damage frequencies in the range of 10^{-7} – 10^{-6} per reactor-year—significantly lower than large LWRs—due to IAEA-based multi-barrier design and passive decay-heat removal requirements (IAEA, 2020a; NEA, 2021b) (L1). SMRs contain smaller radionuclide inventories and rely on enhanced passive safety systems; fuel-system failure is therefore expected to produce only plant-level impacts with limited or no off-site consequences (Sun & Kurosaki, 2025; Lee 2024) (C2).
	GT2. Incomplete or inadequate radiation control	L1	C2	L	L: Measured off-site doses from controlled effluents in Korea remain $< 0.01 \text{ mSv y}^{-1}$, well below the 1 mSv y^{-1} public limit recommended by the IAEA GSR Part 3. International operating experience compiled by the OECD NEA (IAEA, 2025c) and IAEA Safety Report Series No. 104 (2020b) records no significant unplanned effluent-release events in the

Stage	Possible Risk Issue	Likelihood	Consequence	Risk	Remarks
					last decade among operating SMRs or large LWRs. These data support an event probability on the order of 10^{-6} per reactor-year
					C: Continuous containment and filtration systems (HEPA + charcoal beds) ensure that any exceedance results in temporary shutdown and local containment, limiting off-site impacts.
					L: costs are required every year by regulation and practice (labor, surveillance, radiation protection, security, periodic inspections), the likelihood that GF1 pressures appear in any given year is high.
	GF1. High maintenance and safety-inspection costs	L4	C3	H	C: These cost drivers don't usually trigger catastrophic outcomes, but they consistently and materially affect plant economics, cost recovery, and tariff negotiations
	GP1. Uncertainty of SMR integration into PDP	L3	C3	M	"Policy signals for SMR exist (PM 31-May-2024; ERC legal prep Nov-2024; PDP drafts 2025 mention SMR), and 600 MW/2032–2035 targets are discussed, but not yet gazetted in PDP; uncertainty therefore remains possible (L3) and produces material schedule/financing impact (C3) rather than system-wide harm
	GP2. Project uncertainty ("go or no-go") throughout the development phase	L3	C3	M	Multi-step OAP licensing + mandatory EHIA with public hearings make pre-construction schedules intrinsically multi-year; NEA statistics show 0.4–6 yrs per stage internationally, and Thailand's research-reactor case (site 2021 → CL in process 2024–25) confirms plausible delays → L3; effects are material on schedule/finance (EPC, cost of capital) rather than system-wide harm → C3
	GS1. Community opposition arising from radiation concerns	L4	C4	E	Long history of Thai opposition (e.g., 83.4% anti-NPP poll; 2011 indefinite freeze; documented protests) and international experience (Yucca Mountain halted vs Finland's consent-based success) show opposition is likely (L4) and can materially delay or derail siting/licensing and PDP inclusion (C4).
	GS2. Conflicts with communities over issues of public participation	L4	C3	H	Mandatory EHIA public hearings (Ministry of Natural Resources and Environment, 2012) create recurrent disputes in high-impact projects; average review duration 1.5–3 yrs, longer when contested. Weak SLO and prior opposition patterns make conflict likely (L4), while impacts are mainly schedule and transaction-cost delays (C3) rather than national policy paralysis.
	GS3. Threats from warfare or terrorism	L1	C2	L	Malicious-use events are rare (IAEA ITDB: 168 incidents in 2023 with only 6 trafficking/malicious; 147 reports added in 2024). Plants are

Stage	Possible Risk Issue	Likelihood	Consequence	Risk	Remarks
Interim Storage					designed/operated against a Design Basis Threat (IAEA/NRC DBT), which materially lowers success probability. Recent conflict strikes (e.g., Zaporizhzhia) produced no abnormal radiation, indicating bounded source term under safety + security measures → $L1 \times C2$
	ST1. Failure of cooling systems in spent-fuel storage pools	L1	C4	M	Probabilistic risk analyses show SFP loss-of-cooling frequency $\approx 10^{-6}$ per pool-year (for NUREG-1738; NRC 2020). Passive decay-heat removal and redundant pumps make such events rare (L1), but potential radiological release warrants major consequence (C4).
	ST2. System failure caused by natural disasters	L1	C4	M	Seismic studies (NUREG/CR-6865, 5176) indicate dry casks and pools maintain integrity under DBE/BDBE loads—failure probability $< 10^{-6}$ per year (L1). Extreme hazards could still compromise barriers, giving high-impact consequence (C4).
	SF1. High long-term storage and maintenance costs	L4	C3	H	IAEA, 2025c and IAEA TECDOC guides show interim-storage O&M $\approx$ USD 3–4 million per site-year with multi-decade surveillance. Recurring expenditure is certain (L4) and materially affects back-end funding (C3).
	SP1. Absence of a national interim storage facility	L2	C3	M	NEA case reviews find many states relying on extended on-site SNF storage pending repository siting, causing fragmented oversight and schedule risk (L2). Lack of centralized storage increases logistics and cost impacts (C3).
Transportation of waste	SS1. Community concerns near interim storage sites	L3	C3	M	Surveys near interim facilities show only $\approx 58\%$ trust in official info and strong fear of genetic risks (2025 survey). U.S. multi-state data likewise report limited support for local SNF storage. Persistent but localized opposition makes concern possible (L3) with moderate socio-economic consequence (C3).
	TT1. Risk of accident or leakage during transportation	L2	C3	M	Global data (> 300 million shipments since 1960) show zero severe radiological transport accidents (IAEA, 2020a), 2020b). Industrial Type B(U) packages withstand 9 m drop, 800 °C fire 30 min, 15 m immersion, so release risk is low (L2) with bounded impact (C3)
	TF1. High safety and insurance costs for transportation	L4	C2	M	Mandatory insurance and escort provisions under OECD NEA liability conventions raise annual transport costs by ≈ 10 –20 %. Mandatory insurance and escort provisions under RWMA (2009) and OECD NEA liability conventions raise annual transport costs by ≈ 10 –20 %. As these are recurring compliance charges, likelihood is high (L4) but impact moderate (C2).

Stage	Possible Risk Issue	Likelihood	Consequence	Risk	Remarks
	TP1. Ambiguity or lack of clarity in international transport standards	L2	C2	L	IAEA, (2018b) harmonizes land, air and sea modal codes; Thailand OAP applies same standards with minor cross-border gaps. Regulatory ambiguity is rare (L2) and low-impact (C2).
	TS1. Public distrust along transportation routes	L3	C3	M	Public concern about nuclear material transport remains $\approx 40\text{--}60\%$ in international polls (IAEA, 2025c; Office of Natural Resources and Environmental Policy and Planning, 2023). Possible route objections and trust loss make risk possible (L3) with moderate impact (C3)
Final Waste Disposal	DT1. Uncertainty regarding long-term disposal technology (domestic or abroad)	L3	C2	M	Program maturity varies (Finland test-operating ONKALO since Aug 30 2024; Sweden broke ground 2025), while others reversed course (US Yucca terminated per GAO). SSR-5 sets principles, not a single pathway—hence path uncertainty is possible (L3) with planning friction rather than system harm (C2).
	DF1. Investment in repository construction and long-term monitoring	L3	C3	M	Deep Geological Repositories carry multi-decade NEA, (2023) highlights persistent funding/liability duties, then costs recur (L4) and materially affect economics (C3).
	DP1. Lack of a national strategic plan for long-term repository development	L2	C3	M	Thailand's DGR is expected only after 2070, far beyond current SMR deployment. Historical precedent (Finland ≈ 46 yrs; Sweden ≈ 45 yrs to repository start) shows repository funding emerges decades later. Present risk is planning-stage only $\rightarrow$ L2 (low likelihood), but eventual CAPEX/OPEX will be material (C3).
	DS1 – Community resistance to repository site designation	L2	C3	M	No repository site identified yet; community opposition will intensify only once siting proposals emerge (likely after 2070). But eventual local resistance could delay or reshape policy (C3) $\rightarrow$ Medium risk.

Source: Authors' compilation.

Note: L4 – Likely, Almost Certain, L3- Possible, L2 – Unlikely but possible, L1 – Rare, C5 –Catastrophic, C4 –Major, C3 –Moderate, C2 – Minor, C1 –Insignificant

4.4 Recommendations for Risk Management

Based on the risk evaluation, the most urgent priorities for Thailand lie in financial governance, social acceptance, and policy clarity, while technical risks require continued adherence to international safety standards rather than new instruments.

(1) Strengthen Long-Term Financial Governance: High and extreme risks (GF1, SF1, DF1) highlight a systemic gap in Thailand's long-term funding for waste management. To address this, Thailand should adopt a hybrid financing model (Cho & Kim, 2020; IAEA, 2020b; NEA, 2021a; Weibezahn & Steigerwald, 2024; WNA, 2023) 1) short term (pre-deployment): cost-recovery and fee-for-service schemes modeled after Indonesia and Malaysia to cover regulatory and interim-storage expenditures, 2) medium term: introduction of a levy-per-kWh waste charge or an operator-financed "generator-pays" contribution, and 3) long term: establishment of a statutory Radioactive Waste Management Fund, similar to Korea's KORAD, ensuring intergenerational equity and predictable financing for repository development. This approach distributes risk over time and builds fiscal stability before high-cost infrastructure becomes necessary.

(2) Enhance Social License to Operate and Public Participation: Given the extreme and high social risks (GS1, GS2), targeted communication and trust-building strategies are essential: Develop a national nuclear-literacy program led jointly by MHESI, universities, and OAP. Transparency can be strengthened by publishing routinely monitored environmental and radiological parameters, such as ambient gamma dose rates, airborne radionuclide concentrations, surface- and groundwater quality indicators, and operational safety indicators, through publicly accessible platforms. Comparable transparency practices already exist in Thailand, including real-time air-quality reporting by the Pollution Control Department (PCD), water-quality monitoring disclosed through ONEP-supervised EHIA follow-up programs, and environmental monitoring dashboards operated by EGAT for large energy and infrastructure projects. Also possible, apply IAEA TECDOC-1915 recommendations for continuous engagement, rather than episodic hearings. These measures reduce participation-related delays and improve community confidence. These suggestions follow cases around the world; Onkalo repository in Finland, Forsmark in Sweden and Kashiwazaki–Kariwa, Japan.

For the medium- and low-tier risks identified in Table 2, priority actions include strengthening Thailand's nuclear-waste governance through clearer institutional roles, streamlined licensing procedures, and improved inter-agency coordination among the MOE, OAP, ERC, ONEP, MNRE, and future SMR operators. Establishing a single national coordinating mechanism—potentially embedded within existing national energy and nuclear governance structures and led by current regulatory and policy agencies—supported by transparent regulatory timelines, integrated data-sharing platforms, and periodic cross-agency reviews, would reduce policy uncertainty and mitigate governance-related risks. In parallel, Thailand must enhance its technical and organizational capacity for SMR back-end management by investing in human-resource development, specialized training for radioactive-waste operations, emergency-preparedness programs, and independent safety assessments consistent with IAEA GSR Part 5 and SSR-6. Early development of enabling infrastructure—such as centralized interim-storage facilities, transport-readiness systems, and national waste-characterization capabilities—will ensure that the country can safely manage spent fuel from the outset of SMR operation while strengthening public confidence and institutional readiness.

5. Conclusions

This study provides a structured assessment of stakeholders and key risk factors across the SMR spent-fuel and nuclear-waste cycle, integrating both likelihood–consequence analysis and stakeholder perspectives. The risk evaluation shows that technical risks are generally low to medium, reflecting SMR passive-safety design, low global failure probabilities, and well-established operational standards. However, several high-risk factors emerge in the financial, policy, and social dimensions—including long-term storage liabilities, the absence of a clear disposal pathway, regulatory fragmentation, and low public acceptance alongside limited participation mechanisms. These findings indicate that Thailand’s principal challenges lie not in reactor safety but in the institutional, financial, and socio-political conditions that shape back-end readiness. Medium-tier risks, such as uncertainties in future repository planning, transport-readiness gaps, and evolving regulatory requirements, further underscore the need for clearer institutional roles and coordinated governance.

The results collectively show that Thailand’s nuclear future will depend on strengthening the back-end governance system—particularly through establishing a national radioactive-waste management fund. Enhancing community engagement, building trust through transparent environmental reporting, and incorporating international best practices for social-license development are equally essential.

6. Policy Implications

Thailand’s prospective adoption of Small Modular Reactor (SMR) technology requires a policy framework that prioritizes long-term governance capacity, fiscal sustainability, and public acceptance. The findings of this study indicate that the most critical risks associated with spent-fuel and radioactive-waste management are not technical in nature but are instead rooted in financial constraints, institutional fragmentation, and social resistance. As such, policy design should focus on addressing these structural dimensions.

First, Thailand should establish a dedicated national radioactive waste management fund to ensure long-term financial sustainability. Given the intergenerational nature of nuclear waste liabilities, a hybrid financing model is recommended, combining short-term cost-recovery mechanisms, medium-term operator contributions based on electricity generation, and long-term statutory funding arrangements. This approach would reduce fiscal uncertainty and align with international best practices observed in countries such as Korea.

Second, strengthening regulatory coherence and institutional coordination is essential. The current distribution of responsibilities across multiple agencies—including the Ministry of Energy, Office of Atoms for Peace (OAP), Energy Regulatory Commission (ERC), and environmental authorities—creates potential overlaps and delays. Establishing a centralized coordination mechanism, supported by clear regulatory timelines and integrated data-sharing systems, would improve policy consistency and reduce administrative uncertainty.

Third, enhancing social acceptance and public trust is critical to ensuring the feasibility of SMR deployment. Public opposition remains the most significant risk factor, underscoring the importance of transparent communication, continuous stakeholder engagement, and participatory decision-making processes. Policies should promote nuclear literacy, expand access to environmental monitoring data, and adopt international best practices in community engagement to strengthen the social license to operate.

Finally, early planning for back-end infrastructure—including interim storage and long-term disposal—should be integrated into national energy policy from the outset. Proactive policy design in these areas will help avoid future bottlenecks and ensure that Thailand’s energy transition remains both sustainable and economically efficient.

7. Ethics Statement

This study used secondary data from publicly available sources and did not involve human participants, personal identifiable information, or primary data collection. Therefore, ethics committee approval was not required.

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9. Appendix

Table 3. Assessment Schemes for Risk Likelihood and Consequence

Level	Descriptor	Qualitative Criteria (Rubric)
L1 – Rare	Highly unlikely	Event has no historical occurrence in comparable SMR/LWR experience or occurs at frequencies $\leq 10^{-6}$ per reactor-year or shipment; strong engineered and regulatory barriers exist (e.g. passive safety, Type B(U) casks).
L2 – Unlikely but possible	Low probability	Event has occurred internationally under exceptional conditions or is theoretically plausible, but no domestic precedent exists; frequency typically $< 10^{-5}$ – 10^{-4} per year.
L3 – Possible	Credible occurrence	Event has occurred in comparable countries or infrastructure projects, or is expected to arise during multi-year licensing, financing, or public participation processes.
L4 – Likely / Almost certain	Recurring or systemic	Event is structural or unavoidable, such as recurring costs, regulatory delays, or public opposition patterns, and is expected to occur during the project lifecycle.
C1 – Insignificant	Negligible	No measurable radiological, financial, policy, or social impact beyond routine operational variation.
C2 – Minor	Local / reversible	Localized impact within facility boundary; no off-site health impact; limited financial or schedule implications.
C3 – Moderate	Material but manageable	Noticeable financial burden, schedule delay, or public concern requiring management action, but no national policy disruption.
C4 – Major	Severe / strategic	Significant policy delay, long-term financial exposure, or loss of public trust that may affect project viability or PDP alignment.
C5 – Catastrophic	System-level failure	National-scale harm, irreversible environmental or health damage, or collapse of nuclear policy credibility (not observed in assessed SMR back-end risks).

Source: Authors' compilation.