Domestic and International Changes in the Nuclear Environment and Considerations for Establishing Nuclear Safety Regulatory Policy Directions

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1. Introduction

The policy environment surrounding nuclear safety has entered a period of structural transition, shaped by the convergence of technological innovation, the accelerating energy transition, and the evolution of international regulatory norms. Rapid advancements in digital and data-driven technologies, heightened global commitments to low-carbon energy systems, and increasingly institutionalized governance frameworks are collectively reshaping the operational and regulatory landscape within which nuclear safety oversight is conducted.

In anticipation of the Fourth Comprehensive Nuclear Safety Plan (2027–2031), a systematic assessment of these environmental transformations is warranted in order to inform the formulation of forward-looking regulatory policy directions. This study seeks to contribute to that process by adopting a dual methodological approach: (1) a structured analysis of international regulatory and policy trends, and (2) a domestic expert demand survey targeting key stakeholders across nuclear energy, radiation safety, nuclear security, and policy domains.

By integrating these analytical perspectives, the study aims to identify and synthesize core considerations that may guide the development of adaptive and resilient nuclear safety regulatory strategies in a rapidly evolving global context.

2. Review of Domestic and International Trends

2.1 Changes in the Technological, Industrial, Energy, and Nuclear Environment

(1) Expansion of Digital and AI Technologies

Artificial intelligence (AI), automation, and data-driven technologies are increasingly embedded across industrial sectors as general-purpose technologies. In the nuclear field, digital and AI applications are expanding in design, operation, maintenance, and regulatory oversight.

As AI-based diagnostic and decision-support systems become more widely used, regulatory attention may increasingly focus on explainability, data quality, algorithm validation, and lifecycle management. Although these elements have not traditionally been central to nuclear safety standards, their relevance is expected to grow in more digitized operating environments [1].

(2) Supply Chain Restructuring and Security Implications

The global energy transition has intensified demand for critical minerals, while supply concentration and geopolitical tensions have elevated concerns over supply chain resilience.

In the nuclear sector, secure procurement of fuel, safety-grade components, and digital systems, including software supply chains, is gaining importance. Procurement integrity, quality assurance, and cybersecurity considerations may therefore require more systematic integration into regulatory processes. In addition, reshoring and nearshoring trends could affect project costs, schedules, and risk allocation, warranting continued policy attention [2].

(3) Integrated Consideration of Safety and Security

The increasing digitalization of nuclear facilities highlights the interdependence of safety, security, reliability, and accountability. As digital control systems become more prevalent, cyber threats are increasingly recognized as relevant to system stability and continuity of electricity supply. Accordingly, cybersecurity is being viewed as an integral component of nuclear safety governance [3].

(4) Rising Electricity Demand and Power System Transformation

Growing electricity demand and evolving energy mix scenarios may influence the operational role of nuclear power within national energy systems. As part of broader decarbonization strategies, nuclear energy's contribution to grid stability and base-load supply may receive renewed attention.

In this context, nuclear safety regulation may extend beyond facility licensing to address broader operational and system-level considerations. Periodic review of regulatory criteria and oversight mechanisms may therefore be necessary in response to changing energy system dynamics.

2.2 Regulatory Trends in International Organizations and Major Foreign Regulators

(1) Expanding Role of Nuclear Energy and Deployment of Innovative Reactors

International organizations increasingly recognize that nuclear energy may continue to contribute to carbon neutrality and energy security objectives within evolving energy systems [4]. In parallel, a growing number of countries are considering or preparing for the deployment of new nuclear power plants, including small modular reactors (SMRs) and other advanced reactor designs.

As innovative reactor technologies advance from conceptual design to demonstration and early commercialization stages, regulatory readiness has emerged as a central policy issue. The need to ensure that regulatory frameworks are capable of addressing novel technological characteristics without compromising safety standards has become a recurring theme in international discourse.

(2) Regulatory Harmonization and Joint Review Mechanisms

The OECD Nuclear Energy Agency (NEA) has emphasized the importance of regulatory harmonization and the development of joint review mechanisms as SMR technologies approach commercial deploymen [5]. Greater alignment among national regulatory frameworks is viewed as a means to enhance efficiency, reduce duplication of effort, and facilitate consistent safety assessments across jurisdictions.

In addition, the NEA highlights the importance of establishing research priorities and strengthening regulatory foundations in anticipation of potential non-electric applications of advanced reactors, such as hydrogen production, desalination, district heating, and data center operations [6].

The International Atomic Energy Agency (IAEA) similarly notes that SMRs present regulatory considerations distinct from conventional large light-water reactors. These include issues related to modular construction, factory fabrication, staged deployment, commissioning processes, control room staffing configurations, and emergency planning zone design [7] Such distinctions suggest that existing regulatory approaches may require adaptation or refinement, reinforcing the need for sustained international dialogue and coordination.

(3) Strategic Directions of Major Regulatory Authorities: Efficiency, Readiness, and Trust

Major national regulatory authorities have articulated strategic priorities that reflect common themes of efficiency, preparedness, and institutional trust.

The U.S. Nuclear Regulatory Commission (NRC) identifies safety, organizational excellence, and stakeholder confidence as core strategic objectives, emphasizing risk-informed decision-making, data-driven regulatory processes, and the integration of information technologies into oversight functions [8].

France advances a proportionate regulatory approach focused on high-risk activities, coupled with enhanced transparency, accountability, digital transformation, and active participation in international standard-setting processes [9].

Canada underscores modernization, trust, global collaboration, and agility as strategic pillars, highlighting science- and evidence-based decision-making and regulatory readiness to accommodate emerging technologies, including SMRs and advanced systems [10].

Furthermore, the OECD/NEA's medium-term strategy reinforces the importance of international information sharing, identification of common regulatory challenges, maintenance of research infrastructure and technical expertise, and support for the evolution of regulatory processes in response to innovation [11].

Collectively, these strategic orientations indicate a shared recognition that regulatory systems must maintain rigorous safety oversight while enhancing adaptability and coherence in a rapidly evolving technological landscape.

3. Domestic Expert Demand Survey

To inform the formulation of the Fourth Comprehensive Nuclear Safety Plan (2027–2031), a structured demand survey was conducted among domain experts in nuclear energy, radiation safety, nuclear security, policy, and infrastructure. The objective of the survey was to identify strategic directions and priority tasks that should be considered in the forthcoming planning period.

Approximately 30 experts were invited to participate, and 23 responses were obtained, with multiple thematic responses permitted. While the survey was exploratory in nature, it provides insight into prevailing expert perceptions regarding the evolving regulatory environment.

The survey findings suggest that experts broadly perceive the current nuclear regulatory framework as entering a transitional phase. In this context, existing regulatory philosophies and institutional arrangements may face increasing challenges in responding effectively to emerging technological developments, evolving policy landscapes, and strengthening international normative expectations.

Across respondent groups, several environmental factors were consistently identified:

①Expansion of technological diversity, particularly the deployment of small modular reactors (SMRs) and advanced reactor designs;

②Increased integration of digital and artificial intelligence technologies into nuclear systems;

③Intensification of complex and interconnected risks including those associated with climate change, cybersecurity, and broader security threats;

④Growing regulatory demands related to the nuclear fuel cycle, decommissioning activities, and high-level radioactive waste management; and

⑤Strengthening international norms and rising societal expectations concerning transparency, accountability, and institutional trust.

Taken together, these findings indicate a shared recognition among domestic experts that nuclear safety regulation is operating within a more complex and dynamic environment than in previous planning cycles. This perception provides an important contextual basis for considering adaptive and forward-looking regulatory policy directions.

4. Considerations for Establishing Future Nuclear Safety Regulatory Policy Directions

The preceding analysis of domestic and international developments indicates that multiple structural transformations are unfolding concurrently. Digital transformation, supply chain restructuring, the increasing interdependence of safety and security, and evolving electricity demand and market dynamics are interacting in ways that may reshape both the scope and methodology of nuclear safety regulation. These shifts extend beyond isolated operational challenges and suggest the need for a broader strategic perspective in regulatory planning. Accordingly, the formulation of the Fourth Comprehensive Nuclear Safety Plan may benefit from incorporating medium- to long-term environmental considerations alongside immediate regulatory priorities.

International regulatory developments reveal several converging policy orientations. These include strengthening technological neutrality, adopting risk-informed and graded regulatory approaches, enhancing regulatory efficiency, promoting international harmonization, and reinforcing regulatory readiness. Collectively, these trends reflect an effort to preserve predictability, consistency, and safety assurance in the context of accelerating technological innovation. As such, they provide relevant reference points for domestic regulatory policy discussions.

The alignment between international regulatory trajectories and domestic expert perceptions further underscores the likelihood that nuclear safety governance will need to evolve in response to increasing technological diversity and systemic uncertainty. Rather than implying wholesale institutional redesign, this evolution may involve the gradual refinement of regulatory principles, oversight mechanisms, and institutional coordination frameworks.

Several key areas warrant consideration in this context:

① Progressive strengthening of technology-neutral and performance-oriented regulatory approaches to accommodate diverse reactor designs and operational models;

②Development or enhancement of reliability verification frameworks for digital and AI-based systems, including validation, lifecycle management, and cybersecurity integration;

③ Reinforcement of integrated safety and emergency preparedness systems capable of addressing complex and combined risks, including those associated with climate change and cyber threats;

④ Improvement of regulatory coherence across the full nuclear lifecycle, encompassing the fuel cycle, decommissioning, and high-level radioactive waste management; and

⑤ Expansion of international regulatory cooperation and transparency measures to reinforce institutional trust and normative alignment.

In sum, future nuclear safety regulatory policy may be more effectively advanced through a structured and phased approach rather than abrupt institutional transformation. By systematically integrating medium- and long-term considerations into the forthcoming comprehensive plan, policymakers may enhance regulatory robustness, adaptability, and sustained public confidence in nuclear governance under evolving environmental conditions.

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