International Licensing Trends and Regulatory Harmonization for Small Modular and Advanced Reactors

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Abstract

The global development of Small Modular and advanced reactors has accelerated, accompanied by intensified efforts to adapt regulatory systems to new technological and deployment paradigms. However, licensing frameworks originally structured around large, site-specific light-water reactors face structural and procedural tensions when applied to multi-module configurations, factory-based manufacturing, fleet deployment strategies, and non-traditional siting concepts. These tensions do not primarily concern safety objectives themselves, but rather the alignment between established regulatory processes and evolving reactor concepts.

Drawing on recent activities within the IAEA and OECD/NEA, as well as selected national experiences in the United States, Canada, the United Kingdom, and France, this paper analyzes emerging patterns in regulatory modernization and international cooperation. Particular attention is given to three cross-cutting dimensions: (1) regulatory treatment of novel deployment models, (2) the practical implementation of performance-based and goal-oriented regulatory philosophies, and (3) the integration of public acceptance and environmental governance into licensing processes.

Through comparative assessment, the study identifies common structural challenges and areas where regulatory culture, institutional capacity, and legal frameworks shape licensing outcomes. Based on these findings, policy implications are derived for Korea, emphasizing structured pre-licensing engagement, clearer treatment of design stage reviews and manufacturing oversight, systematic use of international regulatory outputs, and strengthened public communication mechanisms. The analysis underscores that regulatory readiness -rather than relaxation of safety standards- is the central determinant of timely and credible deployment of SMRs and advanced reactors.

Keywords: Small Modular Reactors, Advanced Reactors, Licensing, Regulatory Harmonization, Performance-Based Regulation

1. Introduction

Small Modular Reactors (SMRs) have attracted growing international interest as a complement to conventional large nuclear power plants, owing to their potential advantages in modular construction, enhanced and often passive safety features, flexible deployment options, and suitability for non-electric applications such as district heating, hydrogen production, and industrial process heat. As of the mid-2020s, more than seventy SMR concepts are under development worldwide, encompassing a wide spectrum of reactor technologies and levels of design maturity.

Despite this technological momentum, regulatory approval remains one of the most significant barriers to timely SMR deployment. Most existing nuclear licensing frameworks were developed for large, site-specific light-water reactors and do not fully account for distinctive SMR characteristics, including multi-module configurations at a single site, extensive factory manufacturing and offsite assembly, standardized fleet deployment, and potential siting in non-traditional or more densely populated locations. Applying conventional regulatory approaches to these new design risks inefficiency, regulatory uncertainty, and unnecessary delays, even where safety objectives are fully met.

Recognizing these challenges, international organizations and national regulatory authorities have intensified efforts to modernize licensing approaches and strengthen regulatory cooperation. Initiatives led by the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (OECD/NEA), together with national reforms in leading nuclear countries, increasingly emphasize early regulatory engagement, performance-based and goal-oriented regulation, and the systematic use of international regulatory experience.

Against this background, this paper reviews recent international trends in SMR licensing, with particular

emphasis on regulatory cooperation frameworks and selected national experiences in the United States, Canada, the United Kingdom, and France. Based on this comparative analysis, the paper identifies key regulatory issues relevant to SMR deployment and derives policy implications for Korea, focusing on how regulatory readiness can be enhanced while maintaining existing nuclear safety standards.

2. International Frameworks for SMR Licensing and Regulatory Cooperation

2.1 IAEA

i) SMR Regulators' Forum

The IAEA established the SMR Regulators' Forum (SMR-RF) in 2015 to provide a platform for regulators to exchange experience and identify common regulatory issues associated with SMRs. The Forum addresses regulatory challenges across the full lifecycle of SMRs, including design assessment, construction, operation, and decommissioning.

Key topics discussed within the SMR-RF include multi-unit and multi-module licensing, shared safety systems and control rooms, ownership and licensee models, and the application of graded regulatory approaches. The Forum emphasizes that while SMRs introduce novel features, fundamental safety principles remain applicable, and regulatory adaptation should focus on clarity, flexibility, and efficiency rather than lowering safety standards.

This discussion focuses on key issues arising throughout the licensing process of SMRs. The Licensing Issues Working Group examines major regulatory interventions across the SMR lifecycle and analyzes potential challenges in licensing First of a Kind(FOAK) designs compared to Nth of a Kind applications. It also addresses licensing considerations for new build projects involving multiple modules or units, including SMR ownership and licensee models, multi-unit or multi-module licensing approaches, and the implications of shared safety systems, shared personnel, and shared control rooms.

The Design and Safety Analysis Working Group concentrates on technical and regulatory considerations associated with multi-unit and multi-module configurations. Particular attention is given to the application of passive and inherent safety features and the associated analytical and regulatory implications.

The Manufacturing, Commissioning, and Operations Working Group addresses practical aspects essential to the successful deployment and long-term operation of SMRs. Key topics include manufacturability, supply chain management, and commissioning strategies, as well as the systematic collection and effective use of operational experience.

ii) IAEA Nuclear Harmonization and Standardization Initiative

Launched in 2022, the Nuclear Harmonization and Standardization Initiative (NHSI) represents a structured international effort to enhance regulatory cooperation for SMRs and advanced reactors. NHSI Phase I focused on developing common processes for regulatory cooperation, while Phase II aims to support implementation and capture lessons learned.

A major output of NHSI is the Global Framework for Advanced Reactor Reviews (GFARR), which seeks to identify commonalities and differences in regulatory review scopes, criteria, and interpretations. Rather than pursuing full regulatory convergence, NHSI promotes mutual understanding and the effective use of regulatory information generated by other trusted regulators.

iii) IAEA Technical Meetings

IAEA Technical Meeting on Licensing of New Technologies and Approaches to Regulatory Readiness and Cooperation was held in 20~24 October 2025, Vienna, Austria.

The purpose of the meeting is to enhance the knowledge and capacity of Member States by sharing experiences and discussing challenges in relation to the licensing of new technologies, such as SMRs and microreactors, in addition to approaches to regulatory readiness and cooperation.

The meeting was also an opportunity for participants to provide feedback on the tools and publications under development for NHSI Phase II and other IAEA activities.

The brief summary of national presentations and discussions in the meetings are summarized below in section 3 National Regulatory Approaches: Selected Case Studies.

2.2 OECD/NEA

OECD/NEA organized a workshop on "Bridging Law and Technology: International Workshop for the Deployment of Small Modular Reactors" in Stockholm, Sweden, in Dec. 2025. The workshop is structured around five thematic sessions, each focusing on a critical aspect of SMR deployment:

• Authorising SMR designs;

• Pre-licensing and licensing SMRs: siting, environmental reviews and public participation;

• Factory manufacturing, mobile reactors and transportation;

• Maritime applications: propulsion, offshore and onshore power; and

• Fuel cycle, waste management and decommissioning.

The discussions highlight a growing structural gap between rapidly evolving technologies and existing legal and regulatory frameworks. Current legal systems are largely reactive, struggling to keep pace with innovation, which results in regulatory uncertainty, delayed deployment, and potential gaps in safety, accountability, and public trust.

Across jurisdictions and thematic areas, a common conclusion emerges: effective governance of emerging technologies requires a shift from static, prescriptive regulation toward adaptive, collaborative, and forward-looking legal frameworks. Law, technology, policy, and industry must evolve together through continuous dialogue, experimentation, and mutual learning.

3. National Regulatory Approaches: Selected Case Studies

3.1 United States (USNRC)

Since the late 1990s, the U.S. Nuclear Regulatory Commission (NRC) has made meaningful progress through the Reactor Oversight Process (ROP), which successfully applied performance-based (PB) and risk-informed (RI) principles to inspection and oversight. The ROP is widely regarded as a global benchmark and has demonstrably improved industry safety performance. However, similar modernization efforts in licensing and rulemaking have remained incomplete.

Despite clear mandates from Congress—most notably through the Nuclear Energy Innovation and Modernization Act (NEIMA) of 2019 and the ADVANCE Act of 2024—the NRC's regulatory framework continues to rely heavily on prescriptive, probabilistic risk assessment (PRA)-centric requirements. This is evident in the ongoing 10 CFR Part 53 rulemaking, where performance-based attributes are largely underutilized and existing regulatory structures from Parts 50 and 52 are replicated. Institutional resistance to change, legal risk aversion, and insufficient staff training have led to a conflation of "risk-informed" with "performance-based," undermining regulatory flexibility and innovation.

In contrast, international regulators such as those in the United Kingdom and Canada have adopted more objective- and outcome-based regulatory regimes, improving efficiency and enabling advanced reactor deployment. Recent U.S. executive orders issued in May 2025 signal a renewed push for cultural and regulatory reform, emphasizing facilitation of nuclear innovation alongside safety.

Key improvement areas include re-centering regulations on high-level safety outcomes, restoring a clear understanding of PB attributes, expanding applicant flexibility, and aligning U.S. practices with international norms. Advancing true performance-based regulation is identified as a prerequisite for regulatory readiness, efficient advanced reactor licensing, and international harmonization.

3.2 Canada (CNSC)

Canada has emerged as a leading jurisdiction in SMR licensing. The Canadian Nuclear Safety Commission (CNSC) adopted a performance-based regulatory framework and implemented early engagement mechanisms such as Vendor Design Reviews. The use of regulatory hold points during construction has improved regulatory efficiency and predictability.

3.3 United Kingdom (ONR)

The regulatory system provides multiple regulatory pathways for new nuclear projects, including early engagement, Generic Design Assessment (GDA), and site-specific licensing, while maintaining mandatory requirements for nuclear site licensing and regulatory permit across the project lifecycle. This approach is intended to enable innovation while maintaining high safety standards.

In recent years, the UK has strengthened regulatory efficiency through enhanced early engagement mechanisms and modernization of the GDA process. The introduction of tiered Early Engagement and Preliminary Design Review (PDR) processes allows regulators to identify key risks and regulatory gaps at an early stage, reducing downstream licensing delays. The GDA framework has also evolved to better accommodate advanced and small modular reactor technologies by increasing flexibility, allowing staged assessments, and accepting international regulatory submissions where appropriate. These reforms have improved regulatory predictability, reduced duplication of effort, and supported a growing portfolio of advanced reactor projects.

Despite these strengths, challenges remain. UK law

limits the wholesale adoption of international design approvals, requiring project-specific demonstrations of ALARP, which can constrain deeper harmonization. Differences in regulatory expectations between countries still create inefficiencies for vendors pursuing multi-national deployment. Continued improvement is therefore focused on expanding international collaboration, increasing reliance on shared assessments, and further streamlining regulatory interfaces while preserving national legal requirements.

Overall, the UK regulatory regime demonstrates a mature, enabling model that balances safety assurance with innovation. Ongoing improvements in early engagement, flexibility, and international cooperation are central to enhancing regulatory efficiency and supporting timely deployment of new nuclear technologies.

3.4 France (ASNR)

France's nuclear safety regulatory framework, (ASNR) is founded on a technology-inclusive and goal-oriented approach that applies uniformly to all nuclear facilities, including SMRs. Existing regulations -anchored in the French Environmental Code, ministerial orders, ASN resolutions, and Safety Guide No. 22- require a comprehensive safety demonstration as a prerequisite for licensing, without lowering established nuclear safety standards. Based on two years of technical discussions with ten SMR projects, ASNR concludes that the current framework is largely fit for purpose from a nuclear safety perspective.

Innovative or non-PWR features are assessed on a case-by-case basis, allowing flexibility while preserving regulatory rigor. Importantly, no SMR developer identified nuclear safety requirements as regulatory bottlenecks; proposed adaptations largely concerned non-safety areas such as permitting timelines, taxation, or environmental data validity.

However, ASNR identifies a key area for regulatory evolution related to societal acceptability challenges and calls into question whether existing safety objectives -particularly those related to acceptable radiological consequences- are sufficient. Expert and civil society consultations indicate that safety objectives may need to be strengthened for such sites, aiming to demonstrate negligible radiological releases even in severe accident scenarios, thereby avoiding reliance on disruptive protective measures such as evacuation.

4. Key Regulatory Issues in SMR Licensing

Key Regulatory Issues in SMR Licensing identified from the above international activities on the licensing and safety issues of SMRs and advanced reactors from IAEA, OECD/NEA and foreign regulatory bodies are highlighted as follows:

4.1 Novel Deployment Models

SMRs introduce deployment models that challenge long-standing licensing assumptions. These include multi-module facilities operated under a single license, fleet deployment of standardized designs across multiple sites, extensive factory manufacturing with off-site testing or commissioning, and deployment in proximity to industrial facilities or population centers, as well as emerging concepts such as transportable and maritime-based reactors. Such models raise regulatory questions related to shared safety systems, common control rooms, staffing arrangements, configuration management, and the interface between site-based and off-site regulatory oversight.

International experience further indicates that the shift toward factory-based manufacturing and modular construction blurs the traditional boundary between manufacturing authorization and site licensing, creating uncertainty over regulatory jurisdiction, inspection authority, and the mutual recognition of manufacturing approvals across countries. Novel siting options, including repurposed fossil fuel sites, industrial complexes, and border-adjacent locations, also expand the scope of environmental assessment, emergency planning, and liability considerations beyond those assumed for conventional nuclear plants.

International experience underscores the importance of clearly defined regulatory hold points, robust traceability of safety-related manufacturing activities, and unambiguous allocation of responsibilities among designers, vendors, operators, and other stakeholders throughout the reactor lifecycle. Addressing these issues early in the licensing process is essential to maintaining safety while avoiding inefficiencies, duplication, and regulatory uncertainty.

4.2 Performance-Based and Goal-Oriented Regulation

A growing number of regulatory authorities are adopting performance-based and goal-oriented regulatory approaches to better accommodate technological diversity while preserving high safety standards. These approaches emphasize clearly defined safety objectives and expected outcomes, granting applicants flexibility in how those objectives are achieved, which is particularly relevant given the wide diversity of SMR designs, cooling technologies, fuels, and operating concepts.

International discussions highlight, however, that the application of performance-based regulation becomes more complex in areas such as design authorization, generic design assessments, and the treatment of issue finality across different licensing stages and jurisdictions. Variations in national approaches to pre-licensing reviews, combined with limited regulatory capacity and the first-of-a-kind nature of many SMR designs, place additional demands on regulatory staff expertise and institutional readiness.

While performance-based regulation is widely endorsed in principle, its effective implementation remains uneven. International experience demonstrates that success depends not only on regulatory texts, but also on regulatory culture, staff competence, and the availability of clear guidance and cooperative mechanisms among regulators. Without these supporting elements, performance-based frameworks risk reverting to de facto prescriptive practices, undermining their intended benefits and limiting opportunities for international harmonization and reliance.

4.3 Public Acceptance and Transparency

Public acceptance is a decisive factor in SMR deployment, particularly for projects proposed near population centers, industrial sites, or non-traditional locations. Experience from multiple countries highlights the need for early and continuous public engagement, transparent communication of safety objectives and regulatory decisions, and a clear demonstration that existing safety standards are maintained or strengthened for new technologies.

International experience also shows that environmental impact assessment and public participation processes may become more complex for SMRs due to multi-module configurations, cumulative environmental impacts, compressed project schedules, and the applicability of international environmental conventions such as Espoo, Aarhus, and strategic environmental assessment requirements. These factors increase the risk of procedural delays if public engagement is treated as a late-stage or purely formal exercise.

Regulatory approaches that integrate public engagement into the licensing process from an early stage, rather than treating it as a compliance formality, are more likely to build trust and social acceptance. Transparency in how international experience, foreign regulatory assessments, and cooperative review outcomes are used in national decision-making can further enhance regulatory credibility and public confidence.

5. Comparative Assessment and Implications for Korea

The international experience reviewed in this paper demonstrates that the primary challenges in SMR licensing arise not from deficiencies in nuclear safety principles, but from the interaction between novel deployment models, evolving regulatory philosophies, and heightened societal expectations. Across jurisdictions, effective regulatory responses share three common characteristics: early and structured regulatory engagement, credible implementation of performance-based and goal-oriented regulation, and proactive treatment of public acceptance and transparency.

For Korea, these findings suggest several priority areas for regulatory adaptation. First, the diversity of SMR deployment concepts -particularly multi-module sites, fleet deployment, and factory-based manufacturing- requires clearer regulatory treatment of design-stage reviews. The role, legal status, and issue finality of pre-licensing assessments should be clarified to reduce uncertainty for applicants while enabling the regulator to manage first-of-a-kind risks efficiently. Institutionalizing formal pre-licensing review mechanisms would support predictable decision-making and better allocation of regulatory resources. Key Gap and Policy implication for SMRs in Korea are summarized in Table 1.

Second, Korea should anticipate increasing pressure to license SMRs in non-traditional settings, including industrial complexes, repurposed fossil fuel sites, and locations closer to population centers. This shift amplifies the importance of integrating licensing, environmental impact assessment, emergency planning, and public participation processes. Explicit consideration of cumulative impacts from multi-module facilities and early alignment with international environmental obligations will be essential to minimizing procedural delays and societal resistance.

Third, the expansion of factory-based manufacturing and modular construction challenges Korea's predominantly site-based regulatory framework. Regulatory oversight of off-site manufacturing, inspection authority, quality assurance, and traceability of safety-related components -whether produced domestically or abroad- should be strengthened and aligned with international best practices. This is particularly important for advanced fuels and supply chains associated with SMRs and advanced reactors.

Finally, emerging concepts such as transportable and maritime SMRs highlight the need for early examination of potential regulatory gaps related to jurisdiction, licensing responsibility, nuclear liability, and emergency preparedness. Fuel cycle management, radioactive waste disposal, and decommissioning strategies should be addressed explicitly at the design stage, with regulatory and financial assurance mechanisms capable of accommodating modular replacement and phased decommissioning.

Challenge–Response Mapping Table for Corresponding Policy and Regulatory Response for Licensing of SMRs and Advanced Reactors are summarized in Table 2.

Overall, Korea's regulatory adaptation for SMRs should focus on enhancing clarity, flexibility, and institutional preparedness, while firmly maintaining existing nuclear safety standards.

6. Conclusions and Policy Recommendations

International experience confirms that the successful licensing of SMRs does not require lowering nuclear safety standards, but rather strengthening regulatory coherence, adaptability, and readiness in response to new technological and societal conditions. The diversity of SMR designs and deployment models - ranging from multi-module sites and factory-based manufacturing to non-traditional siting and transportable applications- places significant strain on regulatory frameworks originally developed for large, stationary reactors.

The analysis in this paper highlights three cross-cutting regulatory challenges. First, novel deployment models blur traditional regulatory boundaries between design approval, manufacturing oversight, and site licensing, creating uncertainty unless responsibilities and regulatory hold points are clearly defined. Second, while performance-based and goal-oriented regulation is widely endorsed, its effective implementation depends on regulatory culture, staff competence, and clear guidance; without these, performance-based frameworks risk reverting to de facto prescriptive practices. Third, public acceptance has emerged as a decisive factor for SMR deployment, particularly in densely populated or industrial settings, requiring early, transparent, and continuous engagement rather than late-stage procedural compliance.

For Korea, enhancing regulatory readiness for SMRs should be treated as a core element of national nuclear safety policy. Priority actions include institutionalizing structured pre-licensing review processes, expanding regulatory competence in non-light-water reactor technologies, and systematically leveraging international regulatory outputs from trusted foreign authorities and multilateral initiatives. At the same time, clearer separation between policy decision-making and technical regulatory judgment, combined with proactive public engagement, will be essential to building societal trust.

By adapting existing legal and regulatory frameworks to explicitly address SMR-specific characteristics - while maintaining established safety objectives- Korea can position itself to enable the safe, credible, and timely deployment of SMRs in alignment with international best practice.

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Table 1. Key Gap and Policy implication for SMRs in Korea

Regulatory Dimension	Current Situation in Korea	International Best Practice	Key Gap / Policy Implication
Regulatory philosophy	Predominantly prescriptive, LWR-oriented framework with limited SMR-specific differentiation	Performance-based and goal-oriented regulation explicitly tailored to SMRs and advanced reactors	Need for explicit policy endorsement of performance-based, SMR-specific regulatory philosophy
Legal and regulatory basis	Existing Nuclear Safety Act and subordinate regulations applied with incremental interpretation	Dedicated or clearly articulated advanced reactor licensing pathways (e.g., Part 53, flexible GDA)	Clarification or adaptation of legal basis to reduce uncertainty for SMR applicants
Early regulatory engagement	Ad hoc pre-application consultations, limited formal structure	Structured early engagement programs (VDR, Early Engagement, PDR) integrated into licensing lifecycle	Institutionalization of formal pre-licensing review processes within KINS
Design review approach	Plant- and site-specific reviews dominate	Generic or fleet-based design reviews enabling reuse across sites	Need to enable generic design assessment and systematic information reuse
Treatment of multi-module sites	Limited explicit guidance on multi-module and shared systems	Explicit regulatory treatment of multi-module licensing and shared systems (graded approach)	Development of detailed guidance for SMR-specific deployment models
Oversight of offsite manufacturing	Regulatory expectations not fully standardized	Clear regulatory hold points and oversight of factory manufacturing and offsite commissioning	Establishment of regulatory hold points and supply-chain oversight mechanisms
Use of international regulatory outputs	Case-by-case reference to foreign experience	Systematic leveraging of trusted foreign regulatory reviews (SMR-RF, NHSI, GFARR)	Formal framework for accepting and adapting international regulatory information
Regulatory human capital	Strong LWR expertise, limited experience with non-LWR SMRs	Dedicated advanced reactor teams with sustained training and knowledge management	Strategic investment in SMR/advanced reactor regulatory competencies
Public engagement	Compliance-oriented public communication	Early, continuous, and transparent stakeholder engagement embedded in regulation	Shift from reactive communication to proactive trust-building

Table 2. Challenge–Response Mapping Table for Corresponding Policy and Regulatory Response for Licensing of SMRs and Advanced Reactors

No.	Key Challenge	Corresponding Policy / Regulatory Response
1	Mismatch Between Technological Change and Legal Processes	Adopt adaptive, technology-neutral, and risk-informed regulatory frameworks that allow flexibility while maintaining high safety, security, and environmental standards.
2	Fragmentation and Lack of Harmonisation	Strengthen international regulatory co-operation and work-sharing, including information exchange, common principles, and, where legally feasible, mutual recognition or leveraging of assessments.
3	Capacity and Expertise Constraints	Invest in regulatory capacity building and institutional learning, including technical expertise, guidance development, and the use of common terminology and documentation standards.
4	Public Confidence and Participation	Embed transparency, accountability, and meaningful public participation throughout decision-making processes, while streamlining procedures to avoid duplication and consultation fatigue.
5	Unclear Allocation of Responsibilities and Liabilities	Clarify roles, responsibilities, and liability arrangements across the technology lifecycle through clear legal frameworks, early engagement, and co-ordinated regulatory processes.