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Assessing Regulatory Barriers to SMR Deployment in the U.S.: Evidence on LCOE, Investment Risk, and Market Competitiveness

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1. Introduction

The global energy sector stands at a historical turning point, confronted with the dual challenge of achieving carbon neutrality while ensuring energy security. On the one hand, mounting pressure to reduce greenhouse gas emissions in response to climate change is accelerating the demand for low-carbon energy sources. At the same time, geopolitical instability, exemplified by the Russia–Ukraine war, has heightened risks to energy supply security [1]. Against this backdrop, many nations are concentrating their national capacities on securing stable, virtually carbon-free energy options. Nuclear power, alongside renewable energy, has therefore re-emerged as a strategic choice [2].

In particular, Small Modular Reactors (SMRs) have been developed worldwide as shown in Figure 1, since they offer shorter construction periods, lower upfront capital investment, and adaptability to diverse sites and demand environments compared to conventional large-scale light water reactors.

Figure 1 Various types of SMRs

SMRs represent a next-generation nuclear energy supply model that features smaller scale and modularized designs compared to conventional large nuclear power plants, allowing for flexible deployment across diverse sites. SMRs are emerging as a critical alternative in regions with underdeveloped electricity infrastructure, areas expecting rapid demand growth, and contexts requiring decarbonization transitions. Their relatively modest site requirements and modular construction methods can substantially mitigate social conflicts and reduce initial construction risks [3].

Despite their potential advantages, SMRs face greater licensing uncertainty than large land-based reactors. Because nuclear regulations were designed for large LWRs, many requirements remain misaligned with modular designs. For example, criteria for Exclusion Area Boundaries (EAB), Emergency Planning Zones (EPZ), modular licensing, and multi-module safety evaluations are not clearly defined [4,5]. Consequently, SMR projects are prone to licensing delays, which investors view as regulatory risks. These risks raise required returns, increase the Weighted Average Cost of Capital (WACC), and ultimately drive up the Levelized Cost of Electricity (LCOE). [6].

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t = Investment expenditures in year t (including financing)
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of the system

Figure 2 Simplified LCOE formula

The LCOE, calculated as shown in Figure 2, represents the average cost of producing electricity over a plant's lifetime and serves as a key measure of economic competitiveness across energy sources [7]. In recent U.S. nuclear projects, licensing delays and challenges to licensability have increased upfront capital requirements, thereby driving up the LCOE. To mitigate these effects, the Inflation Reduction Act (IRA) of 2022 introduced a Production Tax Credit (PTC) for nuclear power [8, 9].

The durability of current policy support remains uncertain, as political transitions raise the likelihood of changes to tax incentives. The central problem is that unresolved licensing challenges, coupled with unstable fiscal measures, increase capital costs and make both LCOE and investment decisions vulnerable to political shifts. This problem is most evident for SMRs, which are promoted worldwide as a response to growing energy demand and decarbonization. Yet unclear regulatory procedures intensify licensing risks and financing burdens, undermining their economic competitiveness [10, 11].

This study analyzes how uncertainty in licensing, rooted in the mismatch between existing nuclear regulations and the distinctive features of SMRs, drives up the LCOE. It emphasizes the structural constraints in the application of 10 CFR Parts 50 and 52 and examines how these uncertainties in the U.S. setting elevate investor risk and weaken market competitiveness. The purpose is to identify measures that can strengthen licensability and policy stability, thereby lowering costs and supporting investment in SMR deployment.

2. Structural Regulatory Limitations in Applying 10 CFR Part 50 and 52 to SMRs

Nuclear licensing in the United States operates on two primary pathways: 10 CFR Part 50, which separates construction and operation into distinct stages, and 10 CFR Part 52, an integrated framework that links Design Certification (DC), Early Site Permit (ESP), and the Combined License (COL). Table 1 presents a comparison of the two pathways.

Table 1 Comparison between 10 CFR Part 50 and 52

Category	10 CFR Part 50	10 CFR Part 52
Introduction year	1950s	1989
Licensing method	Two-step licensing; (i) construction permit (ii) operating license	One-step licensing; (i) ESP (ii) DC or SDA (iii) COL
Key features	• Flexibility for regulatory changes during construction → higher uncertainty • Application mainly to large LWRs	• Technical and site review at early stage • Minimization of regulatory changes during construction → higher licensing certainty • Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC) requirement
Regulatory burden	• Additional license required before operation • Possibility of prolonged procedures • Relatively low licensing certainty	• High intensity of early-stage review • Documentation and verification through ITAAC • Stronger safety requirements • Higher WACC during construction
Practical use	Research reactors and test facilities	NRC recommended pathway, applied to most new SMRs
Cases	Large reactor construction licensing (e.g., existing LWRs)	NuScale SMR, AP1000, ESBWR, X-energy, Kairos, and other new commercial SMRs
Selectability	Applicant choice regardless of reactor type	

The choice of licensing pathway ultimately rests with the developer, and there is no regulatory mandate tied to the reactor type itself. However, due to the NRC's practical guidance and institutional support, most new commercial reactors tend to pursue the Part 52 route. In fact, large LWRs such as the AP1000 and ESBWR proceeded through design certification and COL under 52, and commercial SMRs such as NuScale have also relied on Part 52 procedures [12]. By contrast, research reactors, non-commercial prototypes, and other first-of-a-kind (FOAK) demonstration units have in some cases applied under Part 50, as illustrated by the Kairos Hermes project.

Part 52 was designed to enhance licensability by requiring that ESP and DC reviews be conducted separately in advance, after which both construction and operation can be authorized simultaneously through a COL. Nonetheless, all inspection and verification requirements must be satisfied prior to the commencement of commercial operation. This creates a burden of front-loaded technical validation and documentation at early stages. As project timelines extend, inspections, quality assurance activities, and responses to Requests for Additional Information (RAIs) from the regulator accumulate, leading to an exponential increase in documentation and verification tasks. This dynamic expands the project management burden on developers, escalates financing costs during construction, and imposes sustained upward pressure on LCOE. Against this backdrop, the drivers of LCOE escalation in SMR licensing can be summarized into four structural regulatory constraints.

2.1. Manufacturing License and the Persistence of Site-specific Requirements

10 CFR Part 50 was originally developed as a regulatory framework for licensing large LWRs. Its two-step process, which separates the CP from the OL, has often created significant uncertainty during construction, since evolving regulatory requirements can impose new obligations after major investments are already committed. This structural inefficiency has historically resulted in licensing delays and cost overruns.

To address these limitations, Part 52 was established as a new framework offering alternative licensing pathways, one of which is Subpart F on manufacturing licenses. In principle, Subpart F allows developers to obtain licensing for the design and factory manufacturing of reactors in advance, so that identical standardized modules can later be deployed at multiple sites. This framework enables design conformity and manufacturing quality to be reviewed once at the licensing stage, reducing the scope of repetitive evaluations during subsequent site reviews.

However, both Part 50 and Part 52 ultimately remain tied to site-specific approvals. For Part 50, site approval is built into the licensing structure from the outset [13]. For Part 52, although the manufacturing license itself is non-site-specific, §52.167 makes clear that a manufactured reactor may only be transported and installed at a site that has already obtained either a CP or a COL. This requirement underscores that SMRs cannot bypass site approval, and therefore the licensing efficiency of Subpart F is inherently limited. In practice, the need to re-engage with site parameters and site-specific regulatory conditions at every deployment site undermines the economies of scale and streamlined timelines that SMRs are designed to achieve.

For investors, this structural limitation translates into heightened risk. They perceive the obligation for repeated site approvals as a regulatory barrier that increases the likelihood of licensing delays, additional RAIs, and extended approval timelines. Such risks drive up the WACC, and these higher financing costs—manifested as interest during construction—are ultimately reflected in elevated LCOE. In this way, the very regulatory framework intended to reduce inefficiency can, paradoxically, constrain the economic viability and competitiveness of SMRs in the marketplace.

2.2. Site Dependency of Emergency Planning

Emergency Planning (EP) represents one of the most critical areas of safety regulation in nuclear licensing. Although the 2023 revision of 10 CFR 50.160 established a performance-based framework for EP applicable to SMRs and advanced reactors, applicants must still demonstrate site-specific adequacy consistent with NRC requirements. As a result, each time a project seeks licensing at a new site, developers must redefine the logic for EPZ boundaries, redesign resident notification and alert systems, secure coordination mechanisms with state, county, and regional medical resources, and conduct periodic drills and joint exercises. These requirements extend beyond formal compliance, imposing recurring costs and schedule uncertainties across planning, institutional agreements (MOUs), and field training.

Conventional large land-based NPPs have been regulated under a fixed-site model, where EPZs are defined according to the surrounding resident population and infrastructure. By contrast, SMRs are designed for modular deployment across diverse sites, which often creates friction with this rigid framework. Even when the same standardized reactor design is used, each site requires new EPZ definition, public hearings, and renewed medical and training arrangements. These repeated obligations dilute the modularization advantage and heighten licensing uncertainty, which in turn amplifies investor risk.

Moreover, SMRs may be deployed in remote or low-population areas under diverse environmental conditions, unlike conventional plants. Applying fixed EPZ radius requirements in such contexts can produce excessively broad and impractical EPZs. This imposes unnecessary costs of negotiation and compliance, ultimately raising both WACC and LCOE.

2.3. Transportation and Jurisdictional Discontinuity

SMRs are designed to be manufactured as modules in factories and subsequently transported for installation at deployment sites, a process that introduces regulatory complexities not typically encountered in large LWRs. Once fabricated, modules may need to move through multiple pathways—including roads, railways, ports, and inland waterways—before reaching their sites. Along this journey, compliance is required with U.S. Department of Transportation (DOT) regulations, and, where applicable, oversight by port authorities and maritime regulators. When nuclear fuel or other radioactive material is involved, additional NRC regulations apply. Standards governing packaging, shielding, resistance to shock, fire protection, and flooding are often overlapping and, at times, inconsistently applied across agencies, creating administrative delays and added regulatory costs.

A further complication is that while a comprehensive international and domestic framework for radioactive material transport exists (e.g., IAEA SSR-6, NRC and DOT adoption of these rules), there is no clearly defined regulatory approach tailored to the unique features of transporting factory-fabricated SMR modules, particularly if fuel is embedded within the module. In such cases, applying existing safety, security, and safeguard (3S) standards—developed primarily for large reactors—may generate unnecessary procedural burdens and interpretive ambiguities. As a result, licensing risks for developers increase, while transport and installation timelines are subject to delays. Ultimately, these factors raise financing costs and impose upward pressure on LCOE, illustrating how transport-related regulatory discontinuities can act as a structural barrier to SMR deployment [9, 12].

2.4. Repetition of Site-specific Requirements

Even when an SMR secures SDA for an identical reactor design, site-specific verification remains mandatory at the stage of construction and operating license applications. This is because requirements such as environmental impact assessments under NEPA, EP under 10 CFR 50.160, and the establishment of EAB under Part 100 and EPZ under Part 50 are inherently tied to the characteristics of each site. Such repetitive verification undermines the efficiency of standardized design deployment and diminishes the economic advantages of replicating SMRs across multiple locations. As a result, site-by-site licensing costs accumulate and exert upward pressure on LCOE [9].

Moreover, reviews under NEPA, physical protection requirements under Part 73, cybersecurity provisions under §73.54, radiation protection standards under Part 20 as implemented in site-specific contexts, and elements of operating programs must all be reassessed in relation to local conditions. When an SMR is deployed at a new site, developers are required to supplement environmental and security plans, conduct integrated site performance tests, perform grid interconnection and isolation tests, and engage in public hearings with local communities. These processes introduce both schedule delays and cost escalation. Compounding this, ITAAC items related to integrated site performance cannot be fully satisfied by factory-level certification alone, thereby expanding the scope of required re-testing [10,11].

In effect, the current regulatory framework prevents SMRs from fully realizing the intended benefits of design standardization and modularization. Instead, it imposes repetitive administrative burdens and amplifies financial risks. This structural limitation constrains the scalability of SMRs and functions as a significant regulatory obstacle to their market competitiveness.

3. Interactions among LCOE, Investor Risk, and Market Competitiveness

One of the most salient challenges in U.S. SMR development is that regulatory uncertainty simultaneously drives up financing and construction costs, while also imposing additional compliance burdens during operation. When regulatory requirements are applied inconsistently or are subject to frequent change, investors perceive heightened risk and demand higher expected returns, while financial institutions increase the project's risk premium. This dynamic elevates WACC, and given the capital-intensive nature of nuclear power, the effect on LCOE is amplified [9].

As LCOE rises, price competitiveness in electricity markets declines, and unfavorable terms emerge in negotiations over long-term power purchase agreements (PPAs). This intensifies sales risk and reinforces investor uncertainty, creating a negative feedback loop. Regulatory uncertainty is thus embedded in credit assessments and risk models, perpetuating an ongoing cycle of risk escalation.

External policy factors, such as uncertainty over the scope and duration of Production Tax Credits (PTC) and Investment Tax Credits (ITC), further exacerbate financing volatility, undermining anticipated reductions in LCOE at the financing stage. When these uncertainties combine with procedural burdens such as construction delays, RAIs, and repeated site testing, financing costs are compounded, and both LCOE and investment risk increase cumulatively [11].

Ultimately, regulatory uncertainty manifests structurally through a chain of interactions: rising WACC, increasing LCOE, expanded investor risk, and weakened market competitiveness. This reinforcing cycle constitutes a critical barrier to the commercial viability of SMRs.

4. Case Studies on Licensing Delays and

Factors of LCOE Escalation

4.1. NuScale (SMR Design Certification under the Part 52 Pathway)

NuScale submitted its SDA application to the NRC in 2017 and in 2020 became the first SMR to obtain design certification. However, even after this milestone, the project was subject to repeated additional verification requirements and RAIs as it navigated evolving electricity demand conditions and regulatory obligations. This regulatory uncertainty also extended to the contractual framework with the Utah Associated Municipal Power Systems (UAMPS), where the price of the Power Purchase Agreement (PPA) rose above initial expectations, significantly amplifying investor uncertainty.

The heightened risk of capital recovery led investors to demand higher expected returns, while financial institutions incorporated greater risk premiums. Together, these dynamics placed upward pressure on NuScale's WACC. Consequently, the LCOE, initially projected at approximately 55 USD/MWh, was reported in 2023 to have risen above 90 USD/MWh during the UAMPS contractual negotiations. This outcome, driven by regulatory delays and increased financing costs, serves as a clear example of how such factors directly contribute to upward pressure on LCOE [14]. The escalation in LCOE eroded NuScale's price competitiveness relative to natural gas and renewables, ultimately leading UAMPS to withdraw from the project in late 2023. This case illustrates the acute vulnerability of SMRs to regulatory uncertainty and compounding financial costs during the early stages of market entry.

4.2. Vogtle 3·4 (AP1000 Construction under the Part 52 Pathway)

Vogtle Units 3 and 4, constructed in Georgia, pursued the Part 52 licensing pathway. However, during the ITAAC (Inspections, Tests, Analyses, and Acceptance Criteria) verification process, repeated design changes and additional regulatory requirements led to prolonged delays in construction. As regulatory uncertainty deepened, financing costs rose sharply, requiring several billions of dollars in additional borrowing beyond the original plan. This heightened investor and lender perceptions of risk, worsened financing conditions, and placed upward pressure on the project's WACC.

The extended delay caused a surge in Interest During Construction (IDC), driving the final LCOE to levels far higher than initial projections. This case makes clear that even for standardized reactor designs, regulatory delays exert a direct and substantial impact on LCOE. The combination of schedule slippage and cost overruns undermined investor confidence in new nuclear projects and created significant hesitation toward initiating further builds [15]. The Vogtle experience thus stands as one of the clearest demonstrations of how regulatory delay and escalating financing costs structurally weaken market competitiveness.

4.3 Kairos Hermes (Demonstration Reactor under the Part 50 Pathway)

Kairos Power pursued its 35 MWth demonstration reactor, the Hermes project, under the Part 50 licensing pathway. This choice reflected the non-commercial nature of the project, but it also imposed the burden of obtaining construction and operating licenses separately in a sequential manner. As a result, even after substantial initial capital had been committed, uncertainty remained over whether an operating license would ultimately be granted. Investors incorporated this "licensing risk" into their assessments and demanded higher expected returns, which placed additional strain on the project's financing structure and exerted upward pressure on WACC.

Because Hermes is a demonstration reactor, direct LCOE calculations are not applicable at this stage. However, the licensing risk it highlights is likely to be carried forward into negotiations over future commercial-scale expansion, where it may be treated as a cost-escalating factor. Thus, the Hermes case illustrates that while Part 50 may be suitable for short-term technology demonstration, it leaves behind unfavorable uncertainties at the financing stage and carries the potential to undermine LCOE competitiveness in the pathway to commercialization.

5. Discussion

The preceding case studies illustrate how regulatory, and policy uncertainties accumulate to increase financing costs, elevate LCOE, and weaken market competitiveness. Regulatory uncertainty manifests in licensing delays and repeated verification demands, raising the cost of capital and driving up WACC. Policy uncertainty, such as doubts over the continuity of tax incentives under the Inflation Reduction Act (IRA), can erode anticipated reductions in LCOE by increasing investor risk. When licensing delays coincide with reductions or eliminations of fiscal incentives, the financial burden on SMR developers rises sharply. This dual uncertainty heightens investor risk perception, leading to more conservative return expectations, restricted capital availability, and diminished market competitiveness.

This analysis shows that the economics of SMRs cannot be determined solely by technological innovation. Their commercial viability depends fundamentally on the suitability of the regulatory framework, the stability of policy, and the licensability of institutional design. Current requirements for EAB, EPZ, transportation safety, and site-specific deployment, developed for large reactors, are often misaligned with the modular and standardized features of SMRs. In addition, the site-bound structure of manufacturing licenses constrains the replication advantages of modularity, and ongoing Part 53 discussions have not yet provided a definitive resolution.

Policy-related factors are directly tied to investor risk. Uncertainty in the continuity of incentive schemes raises expected rates of return, thereby increasing WACC, which drives LCOE higher and undermines competitiveness. Thus, regulatory and policy uncertainties function not merely as procedural issues but as critical barriers to SMR deployment. Commercialization of SMRs therefore requires not only technological development but also an institutional framework that addresses how regulatory barriers shape capital costs and economic feasibility.

6. Conclusions

This study analyzed the regulatory and policy uncertainties affecting the economic viability of SMRs, with a particular focus on the United States. An examination of licensing procedures under 10 CFR Parts 50 and 52, the ongoing discussion on Part 53, and policy instruments such as the Inflation Reduction Act (IRA) shows that regulatory barriers extend beyond procedural complexity. They indirectly increase financing costs through delays and uncertainty, which in turn elevate the LCOE and undermine the market competitiveness of SMRs. The cases of NuScale and Vogtle illustrate cost escalation driven by such factors, while Kairos Hermes demonstrates the interpretive challenges in applying existing frameworks to novel reactor types. Collectively, these cases show that regulatory uncertainty amplifies investor risk perception, leads to a higher WACC, and consequently increases LCOE while weakening competitiveness.

The analysis suggests that SMR economics cannot be determined solely by technological innovation or reactor design efficiency. Their commercial feasibility is fundamentally shaped by the appropriateness of the regulatory framework, the stability of policies, and the predictability of licensing. In particular, existing requirements designed for large light water reactors are often misaligned with SMR modularity and standardization, exacerbating financial and operational risks. Moreover, uncertainties regarding the continuity of tax incentives add complexity to long-term financing.

Nonetheless, the scope of this study is limited by its focus on U.S. cases, which constrains generalization to other countries. In addition, estimates of LCOE and WACC remain highly sensitive to market conditions, political stability, and project schedules. As deliberations on Part 53 are ongoing, the regulatory environment may evolve depending on institutional reforms. Further research should include cross-national comparisons of regulatory systems, analyses of financial structures to mitigate investment risks, and quantitative modeling of how regulatory barriers affect capital costs and competitiveness.

From a policy perspective, promoting SMR commercialization requires enhancing procedural efficiency and establishing a predictable regulatory environment. This entails timely implementation of new licensing frameworks such as Part 53, the stable provision of tax and financial incentives, and mechanisms to share investment risks. If such policy foundations are established, SMRs could secure not only technological innovation but also the economic viability and investment attractiveness needed for deployment.

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