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Does Nuclear Energy Technology Innovation Enhance Uranium Supply Chain Security? Evidence on Domestic Gains and Cross-Border Risks

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Abstract

The global revival of nuclear power raises questions about whether nuclear energy technology innovation strengthens uranium supply chain security. Using a panel of 42 nuclear-related countries and regions from 2007 to 2025, this study constructs a 16-indicator security index covering domestic production and supply, overseas equity resources, domestic resource reserves, and international trade, and measures nuclear energy technology innovation using lagged forward citations to nuclear patents. The results show that innovation significantly improves domestic uranium supply chain security (the baseline coefficient is 0.011, equivalent to about 8.3% of the sample mean). Mediation analysis identifies domestic resource expansion as the most robust channel, with weaker support for production continuity and less stable evidence for overseas equity access. The innovation–security association is stronger where financial development is lower and initial overseas equity holdings are larger. Cross-border estimates provide suggestive evidence of a positive upstream-supplier spillover and a negative downstream-customer spillover, with both results supported mainly at the 10% level. These findings suggest that nuclear innovation can improve domestic uranium security while potentially redistributing benefits and risks across the international uranium supply chain.

Keywords: nuclear energy technology innovation; uranium resources; supply chain security; uranium-production continuity; domestic uranium resources; overseas equity resources

1. Introduction

As the global energy system moves from a singular emphasis on low-carbon transition toward the joint pursuit of decarbonization and energy security, nuclear energy has returned to the center of the energy strategies of major economies. Compared with intermittent renewable sources such as wind and solar power, nuclear power combines a high capacity factor with low life-cycle carbon emissions and stable electricity output. It can therefore provide dispatchable baseload support during deep decarbonization while strengthening energy autonomy, industrial competitiveness, and progress toward climate targets [1–4]. In recent years, the International Atomic Energy Agency (IAEA) has repeatedly revised its projections for global nuclear power development upward, while leading nuclear countries have advanced multiple technology pathways, including large advanced pressurized-water reactors, small modular reactors, fast reactors, and high-temperature gas-cooled reactors. This renewed expansion raises the requirements placed on uranium mining, conversion, enrichment, fuel fabrication, and spent-fuel management. Uranium is therefore no longer

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merely an input to nuclear power generation; it has become a critical resource linking nuclear technological capability, the nuclear industrial system, and national energy security [5,6].

Unlike oil and natural gas, the uranium supply chain is characterized by concentrated upstream resources, concentrated midstream technologies, and technology-specific lock-in downstream. Natural uranium production is highly concentrated in a small number of resource-rich countries; conversion and enrichment capacity is controlled by a limited group of countries with long-standing technological and industrial capabilities; and fuel assemblies are constrained by reactor compatibility, licensing, and quality standards [7–9]. Consequently, national uranium supply chain security cannot be inferred from domestic reserves or the number of import sources alone. It depends on an integrated capacity that combines domestic production, overseas equity resources, strategic reserves, trade-network position, and the various stages of the nuclear fuel cycle. Recent disruptions associated with the Russia–Ukraine conflict, restrictions on nuclear-fuel trade, the substitution of VVER fuel, and bottlenecks in high-assay low-enriched uranium supply further demonstrate that uranium is not traded through a conventional homogeneous commodity chain. Concentration in critical processing, technology, and service segments can rapidly transmit localized shocks across the industrial chain and turn them into systemic risks [10–13].

At COP28, more than 20 countries endorsed the Declaration to Triple Nuclear Energy, which sets an aspirational goal of tripling global nuclear-energy capacity by 2050 [14], while the IAEA's long-term outlook points to sustained expansion [15]. At the same time, nuclear energy innovation is extending beyond incremental improvements in reactor performance to advanced reactor designs, advanced fuels, digital operation and maintenance, and back-end fuel-cycle technologies (the IAEA high-case projection indicates that global nuclear generating capacity could reach approximately 950 GW by 2050, about 2.5 times the 2023 level [15]). Small modular reactors, fast reactors, and other emerging systems impose differentiated requirements on fuel enrichment, fuel forms, fabrication processes, and spent-fuel management [16,17]. Expansion of nuclear generation will also increase uranium demand [18] (the NEA and IAEA project that global reactor uranium demand will rise from about 68,000 tons per year in 2023 to around 86,000 tons per year by 2030, approaching 150,000 tons per year under a high-growth scenario by 2040). More importantly, innovation may reshape the structure and security boundaries of the uranium supply chain by altering exploration and extraction capabilities, fuel-use efficiency, processing-capacity allocation, and cross-border supply relationships. Current challenges involving HALEU availability, VVER fuel substitution, and spent-fuel recycling illustrate how changes in technology pathways affect the entire process from resource acquisition and processing to final utilization. Nuclear energy technology innovation should therefore be viewed not only as an industrial technology variable but also as a structural determinant of uranium supply chain security.

Existing research on uranium resources and supply chain security primarily analyzes these issues from perspectives including resource availability, trade relations, geopolitics, and supply network structures. Some scholars focus on uranium availability and nuclear-fuel assurance by evaluating resource endowments, mining investment, capacity expansion, conversion and enrichment capabilities, and import dependence [19–21]. Some scholars approach the topic from the standpoint of the critical minerals and energy security literature to investigate trade-network structure, supply concentration, geopolitical shocks, and supply chain resilience, emphasizing the roles of network centrality, source diversification, institutional conditions, and substitutability [22–25]. Additionally, some studies focus on nuclear technology innovation and its international diffusion, including technological evolution, patent collaboration, international nuclear-project networks, and technical standards. This literature highlights the cross-organizational and cross-border nature of nuclear inno-

vation and shows that technology exports, project cooperation, and standards can reshape international nuclear-industry relationships [26–29].

Nevertheless, three gaps remain. First, existing explanations largely treat resource endowments, trade dependence, and geopolitical risk as exogenous conditions, paying insufficient attention to how technological progress endogenously expands the boundaries of economically available resources and resource utilization. They therefore cannot fully explain why countries with comparable endowments exhibit different uranium-security capabilities. Second, research on nuclear innovation has concentrated on technological evolution, patent collaboration, and industrial competitiveness, while the channels through which a technological advantage is converted into supply chain security, uranium-production continuity, domestic resource reserves, and overseas equity resources remain underexamined. Third, prior studies generally assess technological benefits from the innovating country's perspective and rarely consider external effects transmitted along cross-border supply chains. Because the nuclear industry is characterized by technology specificity, path dependence, and long-term contracts, greater technological capability in one country may improve its own resource security while simultaneously restructuring the dependencies of upstream and downstream partners. Whether nuclear innovation creates broad-based security gains or redistributes security and vulnerability across countries therefore remains an open empirical question.

To address these gaps, this study uses panel data for 42 nuclear-related countries and regions over 2007–2025 to examine the effect of nuclear energy technology innovation on uranium supply chain security, its underlying mechanisms, and its cross-border risk spillovers. The study makes three contributions. First, it incorporates nuclear energy technology innovation into the analytical framework of uranium supply chain security and extends the literature beyond resource endowments, trade relationships, and geopolitical shocks by considering how technological progress changes resource availability and utilization efficiency. Second, it examines three potential mechanisms through which technological innovation may be converted into uranium supply chain security: improved uranium-production continuity, expanded domestic resource reserves, and enhanced access to overseas equity resources. It also tests heterogeneity using pooled interactions for financial development, initial domestic uranium resources, and initial overseas equity holdings; the panel-robust evidence is strongest for financial development and initial overseas equity, while the domestic-resource pattern is treated as suggestive. Third, it embeds the innovating country in the global uranium supply chain and distinguishes downstream customer countries from upstream supplier countries, thereby bringing domestic security gains and international risk redistribution into a unified framework. The remainder of the paper develops the hypotheses, introduces the data and empirical strategy, presents the results, and concludes with policy implications.

2. Theoretical Background and Hypotheses

2.1. Nuclear Energy Technology Innovation and Uranium Supply Chain Security

Mineral-resource availability theory holds that secure mineral supply does not depend solely on fixed geological reserves; it depends on the capacity to transform potential resources into usable resources under prevailing technological, cost, and industrial conditions [30,31]. Technological progress shifts the economic boundary of resource development, enabling deposits previously constrained by grade, depth, geological conditions, or cost to become economically recoverable [32]. Uranium deposits vary substantially in grade, occur under complex geological conditions, and require long development cycles. Advances in exploration, in situ leaching, integrated mining and metallurgy, and digital mining can increase discovery probabilities and recovery rates while reducing the cost of developing

low-grade or complex deposits [33]. These resource-expansion innovations open new supply sources by moving additional deposits across the technical and economic boundary of recoverability. Moreover, natural uranium must pass through conversion, enrichment, and fuel fabrication before it can be used in nuclear power generation. Innovation in the relevant processes and equipment can ease these processing constraints. Nuclear energy technology innovation can thus improve effective domestic supply from discovery and development to processing and conversion, converting more potential resources into stable, usable supply and strengthening resilience to external volatility or disruption.

Induced technological change theory further suggests that, when critical inputs become scarce or costly, innovation is directed toward improving input efficiency, extending service life, and developing substitutes [34,35]. The resource value of nuclear fuel depends on the effective energy output obtained from each unit of natural uranium. Processing and fuel-cycle innovation extends this efficiency logic to the stages before and after reactor use: improvements in conversion, enrichment, and fuel fabrication reduce material losses and ease bottlenecks. High-burnup fuel, core optimization, online fuel management, spent-fuel reprocessing and recycling, and fast-reactor closed cycles can improve fuel utilization, lengthen refueling intervals, and recover usable nuclear materials from spent fuel [36–38]. For a given level of nuclear electricity output, higher fuel efficiency reduces incremental natural-uranium demand per unit of generation, extends the coverage provided by domestic resources, imports, and strategic inventories, and limits exposure to external procurement and short-term market fluctuations. Nuclear energy technology innovation therefore creates an additional security margin by increasing the usable energy and material services obtained from a given quantity of uranium.

H1. *Nuclear energy technology innovation significantly improves domestic uranium supply chain security through resource expansion and greater processing and fuel-cycle efficiency.*

2.2. The Mediating Role of Uranium-Production Continuity

Operational-resilience theory regards continuity as the capacity to maintain critical functions during a disturbance and restore output within an acceptable period, rather than as nominal capacity alone [39]. This is especially important for uranium production, where ore-body heterogeneity, uncertain leaching conditions, equipment failures, and lengthy mine-development cycles can turn geological endowment into volatile realized output. Nuclear energy technology innovation narrows this gap between potential and realized supply. Advances in geological modeling and resource evaluation improve mine planning; improved in situ recovery and metallurgical processes raise recovery and permit flexible capacity adjustment; and intelligent sensing, process control, and production regulation allow operators to identify and correct abnormal conditions before disruptions become prolonged [33,39]. By making extraction and processing more observable, controllable, and adaptable, innovation increases uranium-production continuity.

Greater uranium-production continuity, in turn, strengthens domestic uranium supply chain security. Uranium mines and processing facilities have long development and restart periods, so output lost during a disruption cannot be replaced immediately. Stable domestic production narrows the recurrent gap between output and reactor requirements, supports predictable scheduling of downstream fuel-cycle stages, and allows commercial or strategic inventories to be replenished under normal conditions. It also reduces emergency purchases in concentrated international markets and preserves a domestic supply option when foreign deliveries are delayed. Because the nuclear fuel chain is sequential, fewer and shorter production interruptions also reduce the likelihood that a local shock will propagate downstream [7,39]. We propose:

H2. *Nuclear energy technology innovation indirectly improves uranium supply chain security by increasing uranium-production continuity.*

2.3. The Mediating Role of Domestic Uranium Resource Reserves

Mineral-resource classification distinguishes uranium occurrences and potential resources from reserves that can be economically recovered under current technological, cost, and regulatory conditions [18,31]. Domestic reserves are therefore not fixed by geology alone. Innovation in geophysical and geochemical exploration, three-dimensional geological modeling, resource estimation, in situ recovery, and low-grade ore processing improves discovery, reduces uncertainty about grade and hydrogeological conditions, raises recovery rates, and lowers development costs. Previously undiscovered, inferred, technically constrained, or uneconomic deposits can thereby enter identified and recoverable reserve categories [31–33,40]. Nuclear energy technology innovation can consequently enlarge the economically recoverable domestic reserve base even when the underlying geological endowment is unchanged.

Larger domestic uranium reserves subsequently improve supply chain security by expanding the country's long-term production options. Reserves do not provide immediate fuel like above-ground inventories, but they support the replacement of depleted mines, development of new production centers, and higher output when import conditions deteriorate. A larger reserve-to-requirement base lengthens the period for which domestic resources can support reactor demand, reduces structural dependence on foreign resources, and strengthens bargaining power in long-term procurement. It also gives governments and uranium enterprises greater flexibility to sequence mine development rather than commit to projects under adverse prices or geopolitical pressure. Evidence on uranium security likewise treats domestic exploration, recoverable resources, and production capability as complements to imports and overseas supply [5,18]. Accordingly, we propose:

H3. *Nuclear energy technology innovation indirectly improves uranium supply chain security by enlarging domestic uranium resource reserves.*

2.4. The Mediating Role of Overseas Equity Uranium Resources

The eclectic paradigm of international production argues that firms invest abroad when their ownership advantages offset the costs and risks of foreign operations [41]. Overseas uranium projects involve substantial geological uncertainty, capital commitments, regulatory requirements, environmental obligations, and political risk. Proprietary capabilities in uranium exploration, resource evaluation, mining, in situ recovery, milling, and fuel-cycle integration reduce project-evaluation and operating costs and make nuclear enterprises more credible partners for host governments and local firms. Technological competence also enables an enterprise to combine resource investment with engineering, processing, safety management, training, and long-term fuel services. It therefore improves access to overseas projects through equity acquisition, joint exploration, mine development, and integrated nuclear cooperation [42–46]. Nuclear energy technology innovation can thereby support a larger portfolio of overseas equity uranium resources.

Overseas equity resources, in turn, enhance the home country's uranium supply chain security. Unlike ordinary market purchases, an equity interest can provide a durable claim on project output, earlier information on production and investment plans, and a basis for coordinating mine supply with domestic fuel requirements. A geographically diversified equity portfolio reduces reliance on a single exporting country or spot market, stabilizes access to long-term volumes, and adds alternative channels when a trade route is disrupted. Foreign ownership cannot eliminate host-country regulation, resource nationalism, or

geopolitical risk, but it increases the home country's control, information, and bargaining capacity relative to arm's-length procurement [25,45,46]. Accordingly, we propose:

H4. *Nuclear energy technology innovation indirectly improves uranium supply chain security by expanding access to overseas equity uranium resources.*

2.5. Cross-Border Risk Spillovers of Nuclear Energy Technology Innovation

The effects of nuclear energy technology innovation extend beyond the innovating country. Because the nuclear industry combines technological specificity, systemic interdependence, and long-term contracts, stronger capability in one country can alter the availability, reliability, and direction of material flows among trading partners, generating international security spillovers.

For downstream customer countries, uranium supply depends on the realized output and processing capability of upstream suppliers rather than on geological endowments alone. Innovation in upstream resource-supplying countries improves deposit identification, extraction and recovery rates, production control, processing capacity, and product quality. These improvements expand economically available supply, increase production flexibility, and reduce the probability and duration of interruptions. Because international nuclear cooperation and fuel procurement connect uranium production with conversion, enrichment, fabrication, and reactor-specific services, the resulting gains reach downstream customers through long-term trade relationships as more stable deliveries and greater replacement capacity [40,47,48]. Upstream innovators may also acquire greater market power, but downstream security improves when the expansion, continuity, and substitutability effects dominate. Nuclear energy technology innovation in upstream countries can therefore generate a positive supply-side spillover for downstream customers.

For upstream resource-supplying countries, uranium mines require large capital commitments, long construction periods, and extended payback horizons. Production, capacity expansion, and continued exploration therefore depend heavily on stable and predictable long-term demand [21,40]. Innovation in downstream nuclear-consuming countries can improve fuel utilization, extend fuel cycles, and increase the recovery and recycling of usable nuclear materials [36,37]. These changes lower the incremental natural-uranium requirement per unit of nuclear generation. A persistent decline in demand from major importers contracts export markets and long-term procurement for traditional upstream suppliers, weakens expected returns to mine expansion and exploration, and may increase dependence on a smaller set of remaining customers. Security gains achieved by downstream innovators may therefore be transmitted upstream as demand uncertainty and market-contraction risk. We propose:

H5a. *Nuclear energy technology innovation in upstream supplier countries improves uranium supply chain security in downstream customer countries.*

H5b. *Nuclear energy technology innovation in downstream nuclear-consuming countries reduces uranium supply chain security in upstream supplier countries by lowering demand for natural-uranium imports.*

The theoretical framework of this paper is shown in Figure 1.

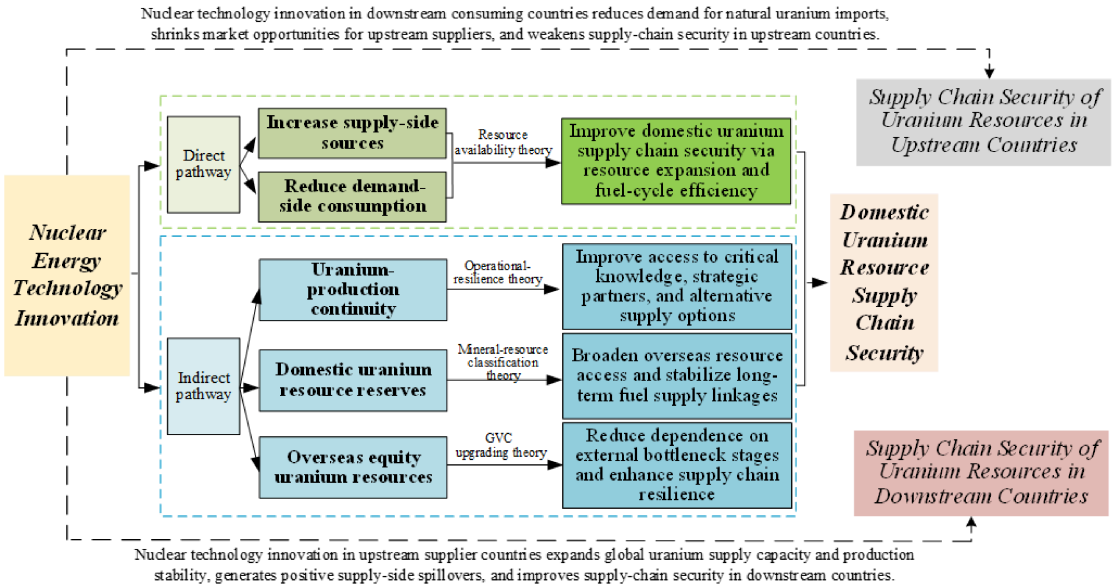


Figure 1. Theoretical framework.

3. Research Design

3.1. Data Sources and Sample Selection

The sample covers nuclear-related countries and regions from 2007 to 2025. After jointly considering the availability of data on nuclear power operation, uranium trade, nuclear patents, and fuel-cycle facilities, the full index-innovation panel contains 798 country–year observations for 42 countries and regions. Country names, regional codes, and annual definitions are harmonized across databases; countries with persistent missing values for the core variables are excluded; continuous variables are winsorized at the 1st and 99th percentiles; and monthly and quarterly observations are aggregated into annual averages or totals. A limited number of short annual gaps are filled by linear interpolation or the most recent observable value. Complete-case samples vary with the availability of lagged controls, mediators, moderators, and partner-exposure measures; the preferred baseline contains 725 observations from 41 countries, and every regression table reports both observations and country clusters. Observations containing imputed values are excluded in a robustness test.

Uranium-resource data are obtained from successive editions of the OECD Nuclear Energy Agency and International Atomic Energy Agency's *Uranium: Resources, Production and Demand* [18]. Annual mine production is compiled from the World Nuclear Association (WNA) and British Geological Survey, and reactor uranium requirements are taken from the WNA and Red Book archives. Bilateral natural-uranium trade is drawn from reporter-side UN Comtrade records for HS 261210 and HS 284410; HS 284420 is excluded because it covers enriched uranium or plutonium rather than the natural-uranium basket examined here. Overseas equity assets are assembled from the project-level uranium-asset register and checked against national nuclear authorities and company disclosures. Reactor and nuclear-electricity information is obtained from the IAEA Power Reactor Information System. Patent data come from EPO PATSTAT and WIPO PATENTSCOPE. Macroeconomic and electricity-structure variables are obtained from the World Bank's World Development Indicators and Worldwide Governance Indicators, and world trade uncertainty is taken from the World Uncertainty Index database.

3.2. Model Specification

To estimate the effect of nuclear energy technology innovation on uranium supply chain security, we specify the following country and year two-way fixed-effects model.

$$SCS_{it} = \alpha_0 + \alpha_1 NTI_{it-1} + \beta X_{it-1} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where SCS_{it} denotes uranium supply chain security in country i and year t, NTI_{it-1} denotes the lagged nuclear energy technology innovation, X_{it-1} is the vector of one-period-lagged controls, and μ_i and λ_t represent country and year fixed effects, respectively. A significantly positive α_1 supports the proposition that nuclear energy technology innovation strengthens domestic uranium supply chain security. The baseline control set contains GDP growth, trade openness, foreign direct investment, log GDP per capita, world trade uncertainty, and clean-electricity share. All main static models report CR1 standard errors clustered at the country level. To account for the moderate number of country clusters, we also report restricted wild-cluster bootstrap-t p-values from 99,999 replications, assigning one Rademacher weight to each country's complete time series. Driscoll–Kraay standard errors with a two-year bandwidth are used as a sensitivity check for residual cross-sectional and temporal dependence.

To identify the transmission roles of uranium-production continuity, domestic uranium resources, and overseas equity uranium resources, we further estimate the following mediation models:

$$M_{it-1} = \theta_0 + \theta_1 NTI_{it-1} + \gamma X_{it-1} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$SCS_{it} = \varphi_0 + \varphi_1 NTI_{it-2} + \varphi_2 M_{it-1} + \eta X_{it-1} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

where M_{it-1} denotes, in turn, uranium-production continuity (PC), domestic uranium resources (DUR), and overseas equity uranium resources $(OEUR)$; NTI_{it-2} is the single-year citation flow two years before the outcome; and X_{it-1} is the vector of one-period-lagged controls. Equation (2) estimates the innovation-to-mediator path, whereas Equation (3) introduces innovation and the mediator jointly into the outcome equation. The indirect effect is $\theta_1 \times \varphi_2$. Its primary inference uses a recursive country-cluster wild bootstrap in which one country-level Rademacher weight is applied to all years and shared by both equations; a whole-country pairs bootstrap that resamples complete country trajectories is reported as a sensitivity check. Both procedures use 99,999 replications.

3.3. Variable Definitions

3.3.1. Uranium Supply Chain Security

Uranium supply chain security refers to a country's capacity to obtain and sustain access to natural uranium under ordinary conditions and external disruptions. It is not interpreted as a direct probability of supply interruption and does not claim to measure every conversion, enrichment, fabrication, or spent-fuel risk in the complete nuclear fuel cycle. Following the composite-indicator logic used in mineral-resource security research [49], we measure four distinct capabilities: domestic production assurance, overseas equity assurance, domestic resource assurance, and international trade assurance.

The baseline index contains four indicators in each dimension, for a total of 16 indicators (Table 1). All indicators are first expressed so that a larger value denotes stronger security. Values are winsorized at the pooled 1st and 99th percentiles and then normalized to [0,1] by min–max scaling on a fixed sample. To prevent dimensions with more indicators from receiving mechanical weight, we use hierarchical CRITIC [50]. CRITIC weights are first calculated within each dimension from an indicator's dispersion and its non-redundancy with the other indicators; the four dimension scores are then weighted by a second CRITIC

calculation. The resulting dimension weights are 0.308 for domestic production, 0.197 for overseas equity, 0.271 for domestic resources, and 0.224 for international trade.

Table 1. Indicator system for uranium supply chain security.

Dimension	Indicator	Measurement	Hierarchical CRITIC Weight
Domestic production assurance	Domestic supply adequacy	min(production/demand, 1) when demand > 0; 1 if production > 0 and demand = 0; otherwise 0	0.074
	Three-year production stability	1/(1 + CV) for production in the current and previous two years; 0 when mean production is zero	0.070
	Annual production non-decline	1 if current output is no lower than the previous year when either year has production; otherwise 0	0.117
	Domestic production scale	ln(1 + domestic uranium production in tU)	0.047
Overseas equity assurance	Equity-weighted overseas asset scale	ln [1 + completed overseas uranium assets weighted by the home enterprise's ownership share]	0.041
	Overseas host-country dispersion	Number of host countries/completed overseas assets; 0 when no overseas asset is recorded	0.077
	Overseas equity supply coverage	ln [1 + equity uranium production/max(domestic uranium demand, 1)]	0.031
	Overseas controlling-interest share	Majority-controlled overseas projects/completed overseas projects; 0 when none is recorded	0.048
Domestic resource assurance	Identified recoverable resources	ln(1 + domestic identified recoverable uranium resources in tU)	0.066
	Two-year resource replenishment	Newly identified resources relative to two-year extraction depletion, truncated to [0, 1]	0.108
	Two-year net resource expansion	Positive growth relative to resources two years earlier; declines set to 0 and growth above 100% set to 1	0.049
	Resource throughput coverage	ln [1 + resources/max(production, uranium demand, 1)]	0.048
International trade assurance	Import-source diversity	1-HHI of supplier shares; 0 when no qualifying natural-uranium import is recorded	0.075
	Three-year import-value stability	1/(1 + CV) for import value in the current and previous two years; 0 when mean imports are zero	0.055
	Supplier breadth	ln(1 + number of supplier countries with positive qualifying imports)	0.040
	International procurement access	ln(1 + import value of HS 261210 and HS 284410 in USD)	0.054

Index sensitivity is assessed with four alternative constructions. We first construct nested 8-indicator and 12-indicator versions containing two and three indicators per dimension, respectively. We then recalculate the 16-indicator index using equal 25% dimension weights and, separately, a single-stage global CRITIC procedure. These alternatives test

whether the baseline result depends on indicator breadth, hierarchical weighting, or the allocation of weight across the four dimensions; the corresponding regressions are reported in Table 1.

Table 1 reports the indicators and their expected attributes.

Figures 2 and 3 present, respectively, the evolution of the composite uranium supply chain security index and its four constituent dimensions for the sample mean and five representative nuclear-energy economies: China, the United States, Russia, France and South Korea. (Figure 2 shows that the sample mean falls from 0.399 in 2007 to about 0.30 after 2015 and then stabilizes. China, the United States and Russia remain above the sample mean in most years, although all three fluctuate; France records the clearest long-run decline, whereas South Korea remains comparatively low. Figure 3 reveals distinct security structures: China and Russia receive more visible support from domestic production and resources; the United States and France have stronger overseas-equity and trade components, although the domestic components of France weaken substantially; and South Korea relies mainly on international trade. Across the full sample, the decline is concentrated in domestic production and international trade, while overseas-equity assurance is comparatively stable and domestic-resource assurance fluctuates within a narrower middle range. These patterns are descriptive, not causal. Because each dimension is normalized, a zero score indicates no positive contribution under the adopted indicator definition rather than the literal absence of all relevant capacity.)

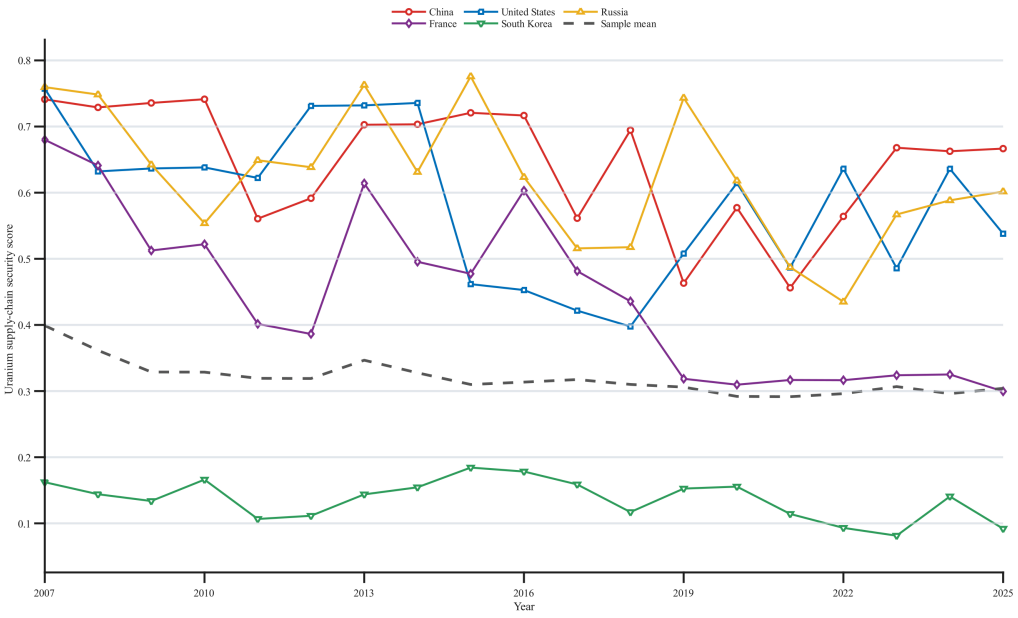


Figure 2. Trends in uranium supply chain security of major nuclear power countries.

3.3.2. Nuclear Energy Technology Innovation

To clarify how the patent-based measures correspond to the physical nuclear fuel cycle, we follow Shang et al. [51] and use Figure 4 to map the chain from uranium resources, mining, milling and recovery through conversion, enrichment, fuel fabrication and reactor use to spent-fuel management, reprocessing and recycling, while marking the stages affected by each innovation category.

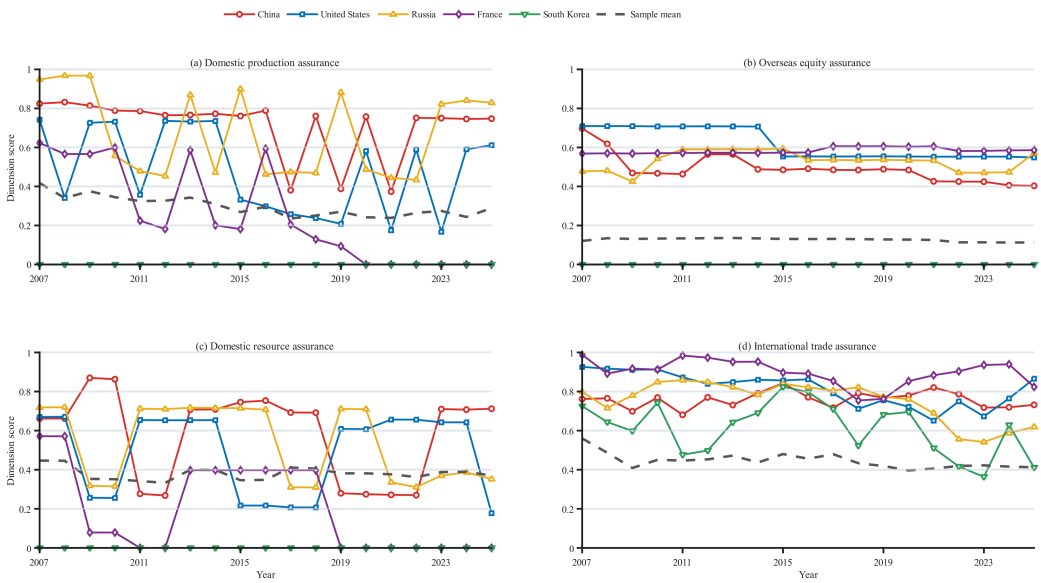


Figure 3. Trends of the four dimensions of uranium supply chain security of major nuclear power countries.

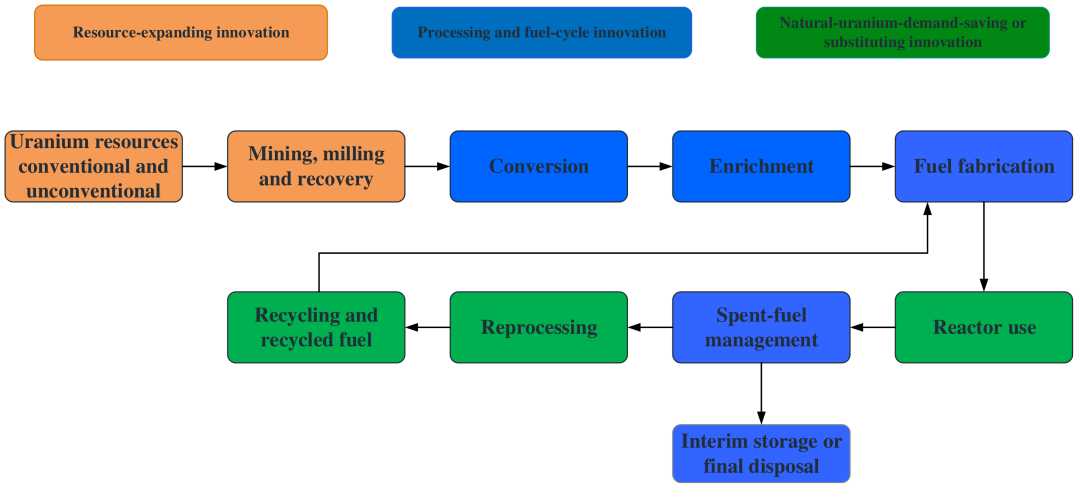


Figure 4. Nuclear fuel cycle and technological coverage of the innovation measures. Note: Colored boxes identify the stages at which each innovation category enters the fuel cycle. A stage may be affected by more than one category, although every patent is assigned to only one category according to its primary technical function.

The patent search is restricted to inventions directly related to nuclear-fission power generation, uranium resources and the nuclear fuel cycle. Identification begins with IPC/CPC groups covering reactors and nuclear-power installations (primarily G21C and G21D), fuel-cycle and radioactive-material technologies (G21F-G21H and Y02E30), and uranium extraction, including C22B60/02. Titles, abstracts and stated technical functions are then screened to exclude medical radiation, isotope tracing and other applications that do not materially affect nuclear power or uranium use. The unit of observation is the PATSTAT application identifier; year is assigned from the earliest reliable priority or filing record, and applicant countries are standardized to ISO3 codes [52].

To capture technological heterogeneity across the fuel-cycle stages, the category analysis distinguishes three substantively different forms of innovation. Resource-expanding innovation (REI) increases the quantity of uranium that can be discovered, recovered or economically accessed, including exploration, in situ leaching, low-grade ore recovery,

phosphate-rock recovery and seawater extraction. Processing and fuel-cycle innovation ($PFCI$) improves the capability, efficiency or reliability of conversion, enrichment, fuel fabrication, fuel inspection, loading, transport, storage, and spent-fuel or waste management without fissile-material recovery. Natural-uranium-demand-saving or -substituting innovation (NUD) lowers fresh natural-uranium requirements per unit of nuclear output or replaces part of those requirements through higher burnup, core optimization, uranium or plutonium recovery and recycling, MOX or thorium use, fast reactors and closed fuel cycles. Each application is assigned to one mutually exclusive category according to its primary technical function. (Each patent application is assigned to one and only one category according to its primary stated function, with the title, abstract and claimed technical purpose taking precedence over broad IPC/CPC codes. Resource-expanding innovation covers technologies that enlarge the accessible uranium resource base, including exploration, conventional and in situ mining, milling, low-grade resources, and uranium recovery from seawater, phosphate rock, tailings and other unconventional sources. Processing and fuel-cycle innovation covers conversion, enrichment, ordinary uranium-fuel manufacture, inspection, loading, transport, storage, and spent-fuel or waste management without uranium or plutonium recovery. Natural-uranium-demand-saving or -substituting innovation covers higher burnup, fuel-utilization and refueling optimization, recovery and recycling of uranium or plutonium, MOX and thorium fuel, fast or breeding reactors, closed cycles, and reuse of depleted uranium or enrichment tails. Thus, ordinary fuel manufacture and non-recovery handling remain in processing and fuel-cycle innovation, whereas recovery or reuse of fissile or fertile material is classified as demand saving or substitution. The mutually exclusive rules ensure that the three category totals add up exactly to total innovation.)

Patent counts alone would assign the same weight to an incremental operating improvement and a potentially transformative fuel-cycle invention. We therefore use forward citations as a proxy for technological influence [53,54]. Citing applications are deduplicated for each target application, and the baseline measure is the natural logarithm of one plus the forward citations received by qualifying applications filed during the three years from $t - 3$ to $t - 1$. The same citation principle is applied to the three innovation categories, which are entered separately in the regressions. The mutually exclusive assignment ensures that their country–year totals add up exactly to total nuclear innovation.

Because forward citations mature gradually and are right-truncated for recent patent cohorts, we separate citation maturation from the economic response lag. Robustness tests therefore use patent counts, a fixed two-year forward-citation window, cohort-age adjustments, exclusion of the 2024–2025 cohorts, and alternative two- to five-year knowledge stocks. These tests assess whether the estimated relationship depends on citation opportunity or on a particular accumulation window.

3.3.3. Mediating Variables

Uranium-production continuity (PC) is measured as $1/(1 + \mathrm{CV})$, where CV is the coefficient of variation of domestic uranium production over the most recent three years. The measure equals zero when the three-year mean production is zero and is lagged by one year in the mediation model. It captures continuity rather than production scale: a country receives a high value when realized output is stable relative to its own mean.

Domestic uranium resources (DUR) are measured as $\ln(1 +$ identified recoverable domestic uranium resources in tU$)$, using the most recent Red Book observation available under the one-year carry-forward rule and lagging the measure by one year. This variable represents the economically and technically identified domestic resource base rather than speculative uranium occurrences or above-ground commercial inventories.

Overseas equity uranium resources (*OEUR*) equal the uranium resources of completed foreign projects multiplied by the ownership shares of home-country enterprises and summed by home country and year. The project-level total is lagged by one year and winsorized at the 1st and 99th percentiles; it is kept in tU rather than logarithmically transformed in the mechanism regression. A zero is assigned only when the project register identifies no qualifying overseas holding. This proxy measures the resource volume to which home-country firms have an equity claim, not merely the number of overseas projects.

3.3.4. Control and Moderating Variables

The preferred baseline includes six theoretically distinct country-level controls, all lagged by one year. GDP growth (*GDPG*) captures the macroeconomic cycle and investment conditions; trade openness (*OPEN*) measures access to international markets; net foreign direct investment inflows as a percentage of GDP (*FDI*) capture cross-border capital exposure; the logarithm of GDP per capita (*GDPPC*) controls for development and technological capacity; the World Trade Uncertainty Index *(WTUI*) captures external uncertainty; and the share of clean electricity in total generation (*CLEAN*) controls for energy-system structure. Using lagged rather than contemporaneous values reduces simultaneous adjustment between uranium security and the controls. Continuous controls are winsorized at the pooled 1st and 99th percentiles. Five- and seven-control variants are retained only as sensitivity tests.

The three moderators are defined consistently with the pooled-interaction design. Financial development is the lagged World Bank measure of domestic credit to the private sector relative to GDP. Initial domestic resources and initial overseas equity holdings are measured as ln(1 + value) in 2007 or the first available pre-treatment observation. Continuous moderators are mean-centered before interaction. Representative low and high values are the 25th and 75th percentiles, except that overseas equity uses zero holdings and the median among countries with positive holdings.

3.4. Descriptive Statistics and Country-Level Transparency

Table 2 reports descriptive statistics for the baseline complete-case sample. The main SCS measure has a mean of 0.323 and ranges from 0 to 0.857. The substantial mass at zero in the citation measures reflects the concentration of influential nuclear patents in a limited set of countries; these are genuine zero counts after applying the technological screen rather than imputed missing observations. The mediation variables are aligned to the outcome year using their one-year lags.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
SCS	725	0.323	0.201	0.000	0.857
NTI	725	1.765	2.445	0.000	8.202
GDPG (%)	725	2.621	3.662	−9.802	10.644
OPEN (%)	725	81.935	44.910	24.480	184.427
FDI (%)	725	3.092	6.479	−22.246	37.356
GDPPC (log)	725	9.414	1.270	6.024	11.336
WTUI	725	0.332	0.687	0.000	3.434
CLEAN	725	0.445	0.301	0.000	1.000
PC	725	0.419	0.449	0.000	1.000
DUR	725	6.615	5.481	0.000	14.413
OEUR (100,000 tU)	725	2.240	5.542	0.000	25.806

4. Empirical Results

4.1. Baseline Results

Table 3 reports the baseline estimates of the effect of nuclear energy technology innovation on uranium supply chain security. Column (1) contains neither controls nor fixed effects; column (2) adds country and year fixed effects without controls; column (3) adds the six lagged controls without fixed effects; and column (4) combines these controls with both fixed effects. Columns (5)–(7) enter resource-expanding, processing/fuel-cycle, and natural-uranium-demand-saving or -substituting innovation in three separate two-way fixed-effects regressions. In the preferred column (4), the coefficient on the lagged three-year citation stock is 0.011 and remains significant with country-clustered inference ($p = 0.037$) and the wild-cluster bootstrap ($p = 0.039$). A one-standard-deviation increase in the stock (2.445) is associated with a 0.027 increase in SCS, approximately 8.3% of its sample mean. H1 is supported.

Table 3. Baseline regression results.

Variable	(1) *SCS*	(2) *SCS*	(3) *SCS*	(4) *SCS*	(5) *SCS*	(6) *SCS*	(7) *SCS*
NTI	0.028 **	0.007	0.024 *	0.011 **			
	(2.68)	(1.30)	(2.39)	(2.15)			
REI					0.008 *		
					(1.73)		
PFCI						0.007 *	
						(2.16)	
NUD							0.006
							(1.34)
GDPG			0.003	0.001	0.001	0.001	0.001
			(1.14)	(0.49)	(0.58)	(0.60)	(0.67)
OPEN			−0.002	0.000	0.000	0.000	0.000
			(−3.06)	(0.90)	(1.30)	(1.14)	(1.14)
FDI			0.002	0.000	0.001	0.000	0.000
			(1.61)	(0.66)	(1.10)	(0.97)	(1.08)
GDPPC			−0.021	−0.045	−0.035	−0.039	−0.035
			(−0.81)	(−1.07)	(−1.17)	(−1.32)	(−1.18)
WTUI			0.015	0.007	0.006	0.007	0.007
			(1.42)	(1.46)	(1.00)	(1.29)	(1.16)
CLEAN			0.027	−0.107	−0.088	−0.100	−0.095
			(0.32)	(−1.63)	(−1.92)	(−2.15)	(−2.04)
Year fixed	No	Yes	No	Yes	Yes	Yes	Yes
Country fixed	No	Yes	No	Yes	Yes	Yes	Yes
Country-clustered SE	0.010	0.005	0.010	0.005	No	No	No
Country-clustered *p*	0.011	0.201	0.022	0.037	No	No	No
Wild-cluster *p*	0.044	0.199	0.073	0.039	No	No	No
Observations	798	798	725	725	725	725	725
Countries	42	42	41	41	41	41	41
R-squared	0.105	0.884	0.299	0.886	0.885	0.885	0.884

Notes: The dependent variable in every column is the 16-indicator SCS. Columns (1)–(4) report CR1 country-clustered inference; restricted wild-cluster bootstrap-*t* *p*-values use 99,999 country-level Rademacher draws. Columns (5)–(7) retain the same six one-period-lagged controls and country and year fixed effects but report conventional homoscedastic inference; country-clustered and wild-cluster inference are not applied in these decomposition regressions. Parentheses report *t* statistics. Significance marks follow the corresponding inference procedure. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.2. Endogeneity and Robustness Tests

4.2.1. Endogeneity Test

To mitigate dynamic endogeneity, following Hahn et al. [55], Higgins and Jochmans [56], and Mei et al. [57], we estimate a dynamic two-way fixed-effects model with lagged SCS and apply a split-panel jackknife (SPJ) correction. The preferred dynamic model uses one-period-lagged predetermined controls and a balanced 2008–2024 panel. Inference is based on 99,999 recursive country-level wild-bootstrap replications, with one Rademacher weight applied to each country's complete time series. (Including lagged SCS captures persistence and reduces reverse-timing concerns; SPJ corrects the leading Nickell bias induced by combining a lagged dependent variable with fixed effects [58], while the recursive bootstrap preserves the model's dynamic structure in finite-sample inference. Thus, coefficient stability after these corrections provides an endogeneity robustness test. GMM is not preferred because, with 42 countries and a moderate time dimension, persistent series may produce weak internal instruments, while instrument proliferation can overfit endogenous variables and weaken Hansen tests.)

Table 4 reports the results. After SPJ correction, the innovation coefficient is 0.010; the recursive country-level bootstrap gives $p = 0.053$, a 90% interval of [0.002, 0.018], and a 95% percentile interval of [0.001, 0.020]. The result therefore provides supportive evidence at the 10% level after accounting for persistence and dynamic fixed-effects bias. In the lead-placebo model, future innovation remains unrelated to current SCS, whereas the predetermined innovation stock remains positive. These tests reduce concerns about reverse timing and dynamic bias, but they are not interpreted as proof that innovation is fully exogenous.

Table 4. Dynamic-panel endogeneity and timing tests.

Variable	(1)	(2)	(3)	(4)	(5)
Model	**Static TWFE**	**Dynamic FE**	**Dynamic FE**	**SPJ-Corrected**	**Lead Placebo**
NTI	0.011 ** (2.15)	0.006 * (1.77)	0.005 (1.25)	0.010 * (1.93)	0.008 ** (1.99)
Lagged SCS		0.269 *** (6.46)	0.290 *** (6.81)	0.459	
Future innovation stock					−0.001 (−0.21)
Controls	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Country-clustered/bootstrap SE	0.005			0.005	
Wild-bootstrap p	0.039			0.053	
Observations	725	578	555	663	696
Countries	41	34	37	39	40
Recursive bootstrap	No	No	No	99,999	No
90% bootstrap CI				[0.002, 0.018]	
95% bootstrap CI				[0.001, 0.020]	

Notes: Columns (2)–(4) use balanced time windows required by the split-panel procedure. Column (4) reports the SPJ coefficient with its recursive country-level wild-bootstrap standard error. The lead placebo in column (5) includes both the predetermined stock and the next-period stock. Parentheses report the relevant t statistic, except that column (4) reports the recursive-bootstrap z statistic for the innovation coefficient.*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.2.2. Additional Robustness Tests

Table 5 reports twelve sensitivity tests. Panel A replaces the baseline outcome with the 8- and 12-indicator indices, fixes the four dimensions at equal weights, applies global CRITIC weighting, and uses five- and seven-control variants. Panel B changes the inno-

vation window and sample by using four- and two-year citation stocks ending in t − 1, excluding major shock years, excluding the most recent patent cohorts, removing the United States, and dropping observations with short-gap imputations. All twelve coefficients are positive and remain significant at the 10% level or better under both country clustering and the wild-cluster bootstrap. The result is therefore not driven by a single index construction, control set, innovation window, exceptional period, dominant innovator, or interpolation rule.

Table 5. Robustness tests.

Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Panel A. Alternative outcome construction and control sets						
Test	8-indicator SCS	12-indicator SCS	Equal dimension weights	Global CRITIC	Five controls	Seven controls
NTI	0.015 ** (2.55)	0.013 ** (2.27)	0.010 ** (2.15)	0.011 ** (2.14)	0.010 * (1.96)	0.011 * (1.98)
Country-clustered SE	0.006	0.006	0.005	0.005	0.005	0.005
Country-clustered *p*	0.015	0.028	0.039	0.038	0.057	0.053
Wild-cluster *p*	0.014	0.028	0.040	0.039	0.056	0.054
Observations	725	725	725	725	727	694
Countries	41	41	41	41	41	40
R-squared	0.898	0.870	0.896	0.898	0.884	0.887
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year/country fixed	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes
Panel B. Timing and sample sensitivity						
Test	Four-year stock ending $t-1$	Two-year stock ending $t-1$	Exclude 2008, 2011, 2022	Exclude 2024–2025	Exclude United States	No interpolated controls
NTI	0.015 ** (2.51)	0.009 * (1.93)	0.012 ** (2.25)	0.011 * (1.82)	0.011 ** (2.16)	0.011 ** (2.13)
Country-clustered SE	0.006	0.005	0.005	0.006	0.005	0.005
Country-clustered *p*	0.017	0.059	0.030	0.077	0.038	0.041
Wild-cluster *p*	0.016	0.055	0.026	0.083	0.039	0.043
Observations	605	725	604	646	707	697
R-squared	0.890	0.885	0.887	0.886	0.887	0.885
Countries	41	41	41	41	40	41
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year/country fixed	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes

Notes: All twelve coefficients are positive and statistically significant at the 10% level or better under both country-clustered and wild-cluster inference. The four- and two-year specifications change the innovation-stock window; all other models retain the baseline three-year stock ending in $t-1$. Country-clustered t statistics are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Taken together, the expanded tests support the sign and statistical stability of the baseline estimate while showing that the coefficient's magnitude varies with the security index and innovation window. As a further check for cross-sectional and temporal dependence, Driscoll–Kraay inference with a two-year bandwidth gives $p < 0.001$ for the baseline coefficient, $p = 0.021$ and $p = 0.092$ for upstream and downstream exposure in the preferred joint spillover model, and $p < 0.001$, $p = 0.010$ and $p = 0.002$ for the financial-development, initial-domestic-resource and initial-overseas-equity interactions, respectively. These checks

do not alter the interpretation based primarily on CR1 and finite-cluster wild-bootstrap inference; in particular, the initial-domestic-resource interaction remains described as suggestive because its wild-cluster p-value is 0.161.

4.3. Mechanism Analysis

To impose a transparent three-wave order, the mechanism regressions use the logarithm of one plus the single-year citation flow in $t-2$, the mediator in $t-1$, and SCS in t. This avoids placing a multi-year innovation stock and the mediator in the same annual interval. Production continuity and domestic resources use six lagged controls for trade openness, log GDP per capita, government effectiveness, nuclear-electricity share, clean-electricity share, and internet use; overseas equity replaces clean-electricity share with manufacturing value added. The indirect effects are evaluated with 99,999 recursive country-cluster wild-bootstrap replications and a whole-country pairs-bootstrap sensitivity check.

4.3.1. Production Continuity

Columns (1) and (2) of Table 6 show that innovation is positively associated with uranium-production continuity, and continuity is positively related to SCS after innovation is retained in the outcome equation. The indirect effect is 0.003. Its country-cluster wild-bootstrap 90% interval is $[0.000, 0.006]$ ($p = 0.072$), and the whole-country pairs bootstrap gives $p = 0.056$; the 95% wild-bootstrap interval includes zero. Technologies for exploration targeting, ore sorting, in situ recovery, hydrometallurgical control, automation, predictive maintenance, and radiation-safe operations can reduce unplanned stoppages and stabilize mine and processing output. More continuous domestic output, in turn, lowers exposure to emergency imports and preserves a reliable domestic supply base. H2 is supported at the 10% level.

Table 6. Bootstrap mediation test results.

Dependent Variable	(1) *PC*	(2) *SCS*	(3) *DR*	(4) *SCS*	(5) *OER*	(6) *SCS*
NTI	0.020 *	0.004	0.222 **	0.004	0.233 *	0.004
	(1.73)	(1.13)	(2.34)	(1.18)	(1.73)	(1.02)
PC		0.154 ***				
		(6.99)				
DR				0.012 ***		
				(3.78)		
OER						0.004 ***
						(3.91)
Indirect effect		0.003 *		0.003 **		0.001 *
WCB 90% CI		[0.000, 0.006]		[0.001, 0.004]		[0.000, 0.002]
WCB 95% CI		[−0.000, 0.006]		[0.000, 0.005]		[−0.000, 0.002]
WCB p-value		0.072		0.012		0.076
Country-pairs p-value		0.056		0.038		0.139
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	693	693	693	693	662	662
Countries	40	40	40	40	39	39

Notes: OEUR is rescaled to 100,000 tU; the indirect effect is invariant to this rescaling. Country-clustered t statistics are shown in parentheses. WCB is a recursive country-cluster wild bootstrap using one common country weight across all years and both equations; pairs resample complete country trajectories. Both procedures use 99,999 replications. Interval endpoints are rounded to three decimals; statistical inference uses the unrounded bootstrap draws. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.3.2. Domestic Identified Resources

Columns (3) and (4) of Table 6 show that innovation expands identified recoverable domestic resources, while a larger resource base improves SCS. The indirect effect is 0.003, and both its 90% [0.001, 0.004] and 95% [0.000, 0.005] country-cluster wild-bootstrap intervals exclude zero ($p = 0.012$). The whole-country pairs bootstrap also supports the channel ($p = 0.038$). Advanced prospecting, resource modeling, low-grade-ore recovery, and improved leaching can convert geological occurrences into economically and technically identifiable resources. A larger recoverable base lengthens domestic coverage and provides a physical buffer against external disruptions. H3 is supported.

4.3.3. Overseas Equity Resources

Columns (5) and (6) of Table 6 show a positive innovation-to-overseas-equity path and a positive mediator-to-SCS path. The indirect effect is 0.001; its country-cluster wild-bootstrap 90% interval is [0.000, 0.002] ($p = 0.076$), whereas the 95% interval includes zero and the whole-country pairs bootstrap does not reject zero ($p = 0.139$). Technological competence can improve project appraisal, processing design, operating credibility, and bargaining capacity, helping domestic firms acquire or develop foreign uranium assets. Equity claims provide access and optionality that are less exposed than arm's-length purchases to spot-market scarcity.

4.4. Heterogeneity Analysis

Heterogeneity is tested with the same pooled interaction specification in all four cases. The formal evidence is the coefficient on innovation × moderator, not a comparison of significance levels from separate subsamples. Continuous moderators are mean-centered; marginal effects are reported at representative low and high values. The regression results are shown in Table 7.

Table 7. Heterogeneity analysis.

Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Moderator	Financial development	Financial development	Initial domestic resources	Initial domestic resources	Initial overseas equity holdings	Initial overseas equity holdings
Reported quantity	Interaction	Marginal effect	Interaction	Marginal effect	Interaction	Marginal effect
Innovation × moderator	−0.059 ***		0.001		0.053 **	
	(−3.16)		(1.81)		(5.43)	
Innovation effect: low		0.032 ***		0.000		0.007
		(3.28)		(0.04)		(0.96)
Innovation effect: high		0.004		0.016 ***		0.033 ***
		(0.50)		(3.41)		(4.67)
Country-clustered SE	0.019		0.001		0.010	
Country-clustered p	0.003		0.078		0.000	
Wild-cluster p	0.008		0.161		0.045	
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year/country fixed	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes	Yes/Yes
Observations	564	564	725	725	525	525
Countries	41	41	41	41	39	39

Notes: Interaction coefficients provide the formal tests of heterogeneity. CR1 standard errors are clustered by country; wild-cluster p-values use 99,999 country-level Rademacher draws. For overseas equity, the low value is zero holdings, and the high value is the median among countries with positive holdings; the other marginal effects use the 25th and 75th percentiles. Country-clustered t statistics are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4.4.1. Financial Development

The interaction with financial development is negative and significant. The marginal innovation effect is 0.032 at the 25th percentile and 0.004 at the 75th percentile. This pattern

is consistent with a compensating role for technological capability where private credit is scarce: innovation can relax engineering and operating constraints that cannot readily be offset by financing, whereas countries with deeper financial systems possess more procurement, inventory-financing, and risk-management alternatives.

4.4.2. Initial Domestic Uranium Resources

The interaction with initial domestic resources is positive and reaches the 10% level with country-clustered inference, but not with the finite-cluster wild bootstrap. The marginal innovation effect is near zero at the 25th percentile and equals 0.016 at the 75th percentile. The pattern is consistent with complementarity between innovation and geological endowment, but it is treated as suggestive rather than as a panel-robust heterogeneity finding.

4.4.3. Initial Overseas Equity Holdings

Initial overseas equity holdings are measured by the logarithm of one plus the equity-weighted number of completed foreign uranium projects at the beginning of the sample. The interaction is positive and remains significant with both country clustering and the wild-cluster bootstrap. The innovation effect is 0.007 for countries without an initial holding and 0.033 at the median among positive holders. Existing overseas assets thus provide an organizational and contractual platform through which technical competence can be converted into additional supply access.

4.5. Further Analysis: Cross-Border Technology Spillovers

The spillover variables are constructed at the focal-country–year level. For focal country i in year t, upstream exposure is the weighted mean of innovation in countries j that supplied i's natural-uranium imports, and downstream exposure is the weighted mean of innovation in countries k that purchased i's natural-uranium exports. Bilateral trade is restricted to HS 261210 and HS 284410. Lagged trade-value shares are used as weights, partner innovation is measured before aggregation, and weights are renormalized only when matched partners represent at least 50% of the focal country's relevant trade value. Patent-count exposure is $\ln(1 + \text{partner patents})$ before aggregation; the citation alternative uses $\ln(1 + \text{partner forward citations})$. Each SCS observation therefore enters only once per country–year, rather than being repeated for every bilateral pair. The regression includes own innovation, the partner exposure or exposures, the stated controls, and country and year fixed effects.

Table 8 reports the estimates. In the preferred joint patent-count model, upstream innovation exposure has a positive coefficient of 0.005, whereas downstream exposure has a negative coefficient of −0.006. Both coefficients have the expected signs but are supported mainly at the 10% level under country clustering and the finite-cluster bootstrap. The signs are unchanged when the controls are removed and when partner citations replace partner patent counts, although precision varies across these sensitivity specifications. Taken together, the results provide suggestive support for H5a and H5b.

The positive upstream coefficient is consistent with supplier-side innovation improving the reliability, recoverability, and service quality of uranium available to importing countries. The negative downstream coefficient captures a different transmission direction: innovation among customer countries can raise burnup, recycling, fuel efficiency, or substitution, thereby reducing expected natural-uranium demand and weakening the production incentives and revenue stability of exporting suppliers. The two signs are therefore not contradictory; they correspond to supply-reliability gains moving downstream and demand-contraction pressure moving upstream.

Table 8. Country–year cross-border technology spillover results.

Variable	Joint Model
Dependent Variable	***SCS***
Upstream innovation exposure	0.005 * (1.90) [0.052]
Downstream innovation exposure	−0.006 * (−1.78) [0.091]
Own NTI and baseline controls	Yes
Country/year fixed effects	Yes/Yes
Observations	326
Countries	32

Notes: The dependent variable and control specification are unchanged: the 16-indicator SCS and the baseline six one-period-lagged controls are used. Upstream and downstream innovation exposure enter the same regression together with focal-country NTI and country and year fixed effects. Country-clustered t statistics are reported in parentheses; wild-cluster *p*-values based on 99,999 country-level Rademacher draws are reported in square brackets. Significance marks follow the wild-cluster *p*-values. * indicates significance at the 10% level.

5. Conclusions and Policy Implications

Using a panel of 42 nuclear-related countries and regions from 2007 to 2025, this study finds that nuclear energy technology innovation improves national uranium supply chain security, and the result remains supported by country-clustered, wild-cluster, robustness, and dynamic-bias-corrected inference. Mediation analysis identifies domestic resource expansion as the most robust channel, with weaker support for production continuity and less stable evidence for overseas equity access. The innovation–security association is stronger where financial development is lower and initial overseas equity holdings are larger, while the initial-domestic-resource pattern is suggestive. Cross-border analysis provides suggestive evidence of asymmetric spillovers: upstream supplier-country innovation is positively associated with downstream partners' security, whereas downstream customer-country innovation is negatively associated with upstream suppliers' security.

The evidence suggests the following policy priorities.

First, governments should integrate uranium supply-security objectives into nuclear innovation policy. Funding should prioritize resource-expansion and fuel-cycle technologies and link R&D, pilot testing, and industrial deployment through joint roadmaps among research institutes and industry. Evaluation should emphasize resource additions, recovery and fuel-use efficiency, facility reliability, and fewer production interruptions rather than patent counts alone.

Second, policy implementation should focus on the three channels through which innovation is converted into supply security. Operators should strengthen process monitoring and preventive maintenance; resource authorities should sustain geological surveys, reserve reassessment, and low-grade recovery demonstrations; and public financial institutions should combine due diligence, long-term finance, and political-risk insurance for viable overseas equity projects. An interagency mechanism should monitor production continuity, domestic resource additions, and equity supply and address emerging bottlenecks early.

Third, innovation support should be differentiated across countries and coordinated along the international uranium supply chain. Finance-constrained countries need patient capital and risk sharing; resource-endowed countries should connect R&D to deposit-specific constraints; and holders of overseas assets should coordinate production, transport, inventories, and procurement. To manage asymmetric spillovers, suppliers and customers

should expand joint technical programs, share medium-term demand information, and use flexible long-term contracts or joint development arrangements.

Several limitations provide directions for future research. Country-level indicators cannot fully capture contracts, spare capacity, or recovery after disruptions, while patents imperfectly reflect commercial deployment. Annual panel estimates also cannot eliminate every source of endogeneity or reveal project-level mechanisms. Future research could combine firm- and project-level data with disruption events and quasi-natural policy shocks.

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