Uranium at the nexus of energy security and sustainable development in a renuclearised world: demand trajectories and technological pathways

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Supplementary Note 1: Summary of 2040 reactor fleet and reactor-related uranium requirement scenarios

Table S1 compiles global 2040 totals that are either reported directly or compiled/estimated from scenario tables. Reactor-related uranium requirements (tU/yr) are expressed in tonnes of uranium metal per year. Where reports do not explicitly provide tU/yr (e.g., IEA), values are author-estimated using a fleet-average conversion of 160 tU per GWe per year (consistent with NEA/IAEA Red Book conventions). Scenario assumptions that materially affect tU totals include: (i) New-build schedules and commissioning years, (ii) Lifetime-extension assumptions for operating reactors, (iii) Capacity factors and average burn-up, (iv) SMR/advanced reactor share (fuel type may differ, especially HALEU), and (v) Fleet mix (PWR, PHWR, LWR shares).

Values in the table reflect the ranges reported in the source materials; differences across sources are due to treatment of announced/planned builds, assumed retirements, and assumptions regarding SMR/advanced reactor deployment. The table provides a quantitative anchor for analysis of uranium demand trajectories in a renuclearised world.

Table S1: Summary of published 2040 reactor fleet and reactor-related uranium requirement scenarios from four principal sources: NEA/IAEA Red Book, IAEA, World Nuclear Association, and the IEA

Source	Scenario (label used in report)	Installed capacity (GWe)	Reactor-related U requirement (tU/yr)	Key assumptions/notes
NEA/IAEA Red Book - Uranium 2024: Resources, Production and Demand [1]	Low Reference High	~ 486 ~ 708 ~ 931	~ 56,640 - 100,224	The Red Book uses a fleet-average fuel intensity of approximately 160 tU/GWe/yr, driven by scenarios based on reported country plans, retirements, and fuel-use factors. Projections are driven by reported country plans, expected retirements, and generic fuel-use factors.
IAEA- Nuclear Technology Review 2024 / PRIS-based projections [2, 3]	IAEA low vs high demand scenarios/ PRIS-based projections	~ 512 ~ 679	~ 63,040 - 108,272	Based on PRIS fleet projections, announced builds, retirements, tU/yr calculated from reported capacity × fleet-average fuel intensity.
World Nuclear Association - World Nuclear Fuel Report 2025 [4, 5]	Lower Reference Upper	~ 552 ~ 746 ~ 966	~ 107,000 ~ 150,000 >204,000	Derived from reported scenario capacity and fleet mix; includes planned builds, lifetime extensions, SMR/advanced reactors; tU/yr uses WNA assumptions*.
IEA - The Path to a New Era for Nuclear Energy (2025) [6]	Stated Policies Accelerated Growth	~ 634 ~ 931	~ 101,440 ~ 149,000**	Uranium requirement estimated using 160 tU/GWe/yr conversion; IEA scenarios include SMR deployment (~ 10 % by 2040), retirements, and new builds**.

*WNA scenarios place a stronger weight on announced/planned builds and extended lifetimes than the Red Book low case. **Estimated in this study using NEA/IAEA fleet-average conversion for comparability.

Supplementary Note 2: Summary of near-term nuclear power projects and emerging SMR deployments

Table S2 presents a selection of near-term national nuclear power projects and early small modular reactor (SMR) initiatives that have been publicly announced or are under active development as of 2024-2025. The table aims to capture the global distribution of current nuclear build programmes, providing a representative overview of both large-scale gigawatt-class reactors and emerging SMR technologies across diverse regional contexts.

The selected entries illustrate variations in reactor typology, procurement strategies, and indicative commissioning timelines, thereby offering insight into the dynamics of contemporary nuclear expansion and uranium demand trends[1, 7, 8]. The commissioning windows listed are approximate and should be interpreted as indicative only. They are derived from publicly available planning targets, regulatory filings, and vendor schedules rather than binding contractual commitments. Consequently, these projections remain contingent on project financing, supply-chain capacity, regulatory approvals, and evolving geopolitical circumstances.

Project status summaries are based on international institutional reporting and peer-reviewed analyses of nuclear deployment and SMR readiness[9–12]. Together, these data provide a timely snapshot of the shifting global nuclear landscape, reflecting how diverse national programmes are progressing toward a new phase of renuclearisation.

Table S2: Selected near-term nuclear projects and status showing public project statements; commissioning windows are indicative and depend on financing, supply-chain, and regulatory outcomes

Region	**Country**	**Reactor type/capacity**	**Status**	**Indicative commissioning window**
Africa	Egypt -El Dabaa [13]	4 × VVER-1200 (4×1 200 MWe)	Under construction; major civil works and RPV assembly underway	Unit-by-unit commissioning across mid-2026 → early 2030s (phased)
Asia	Vietnam / Indonesia [14]	Various (large PWR concepts; SMRs being considered)	Feasibility, regulatory development, and siting: policy steps underway	First-of-a-kind projects targeted in 2030s (country specific)
	Bangladesh - Rooppur [15]	2 × VVER-1200 (2 × 1 200 MWe)	Final commissioning tests / hot functional testing underway	First commercial unit late 2025 to early 2026; second unit shortly thereafter
Middle East	UAE -Barakah [16]	4 × APR-1400 (4×1 400 MWe)	Fully operational (all units commercial)	Commercial operation completed (latest unit 2024)
Europe	Poland-Lubiatowo-Kopalino (PEJ) [17]	3 × AP1000 (3 × 1250 MWe) (first national project)	Site studies and engineering development; notified to EC	Targeting mid-2030s for first unit (programme span 2033-2036 or later, depending on financing)
	Czech Republic - Temelín/ Dukovany (SMR & large reactor options) [18]	Temelín: SMR (Rolls-Royce SMR) early-works; Dukovany: APR-1000 procurement	Early works agreements / preferred bidders concluded	SMR early-deployments early-to-mid-2030s (site-specific work ongoing)
	Hungary-Paks II [19]	2 × VVER-1200 (planned)	Contracted to Rosatom; subject to EU legal challenge on state aid	Timeline previously targeted early-2030s; legal ruling complicates aid approval
South America	Argentina / Brazil	Argentina: CAREM (SMR prototype) / Atucha/Embalse operations; Brazil: Angra-3 (delayed)	CAREM prototype and research reactor roadmaps; Angra-3 remains contested/finance-constrained	CAREM/SMR pilot by late 2020s → 2030s (if funded); Angra-3 uncertain (multi-decade timelines)

Reactor capacities are expressed as gross electrical power (MWe) where reported; expected commissioning windows are approximate and reflect publicly reported planning targets or regulatory/permitting expectations.

While global uranium demand growth is concentrated in a few large markets, significant incremental demand is also opening in regions previously peripheral, thereby reinforcing the supply-chain, resource-security, and geopolitical dimensions of the uranium-fuel cycle.

Table S3: Indicative regional uranium-demand growth, 2030 - 2045

Region	**2025 annual reactor-uranium requirement (tU/yr)**	**Indicative range in 2035–2045 (tU/yr)**	**Key assumption drivers**
Asia (incl. China, India, Vietnam, Indonesia)	~30,000	~45,000-70,000	Rapid new build + lifetime extensions + higher capacity factors
Americas (North + South)	~12,000	~18,000-28,000	New SMRs, licence extensions, and new-builds in Latin America
Europe (incl. newcomer states)	~10,000	~14,000-22,000	SMR deployments + refurbishment, moderate fleet expansion
Africa & Middle East	~5,000	~8,000-15,000	First-of-a-kind nuclear builds, newcomer programmes, and regional entry of SMRs

Assumptions: fleet-average natural-uranium intensity is placed within 150-170 tU/GWe/yr; capacity-factor improvements of +5 to 10 power plants are assumed; average new-build unit size ~1 GWe (LWR/SMR mix); regional commissioning rates consistent with national roadmap announcements and international agency outlooks such as NEA/IAEA.

Supplementary Note 3: SMR uptake sensitivity, assumptions, and implications for uranium demand to 2040

Table S4 summarises the three uptake bands (low, mid, high), the associated licensing and cost-learning assumptions, factory throughput estimates, and the implied incremental uranium requirements through 2040, providing a transparent linkage between technology diffusion and fuel-cycle demand. The assumptions underlying Table S4 draw on a synthesis of international agency scenarios, peer-reviewed analyses, and recent policy developments. The IEA's Path to a New Era for Nuclear Energy report (2025) provides the upper-bound benchmark, in which SMRs could represent roughly 10 % of global nuclear capacity by 2040 (~ 60-100 GWe) under accelerated policy and investment conditions [6]. This forms the basis of the high-uptake scenario. In contrast, the NEA SMR Dashboard and IAEA SMR Platform highlight persistent constraints, licensing bottlenecks, component certification, supply-chain immaturity, and limited factory throughput, which may restrict near-term scale-up [1, 7, 20]. These institutional insights define the low and mid-range cases, which assume slower regulatory progress and fewer operational assembly lines before 2040. Recent peer-reviewed modelling studies report learning rates of 10-20 % per cumulative doubling of output, implying potential NOAK cost reductions of 10-50 % depending on the achieved factory throughput and design standardisation [21–28]. Finally, recent policy announcements, such as the U.S. NRC's streamlined licensing pathways and government procurement guarantees in Canada, the UK, and South Korea, inform the optimistic end of the licensing-delay range used in the high scenario. Together, these sources provide a realistic envelope for SMR uptake sensitivity and its implications for uranium demand.

Table S4: SMR uptake sensitivity (scenarios and assumptions) and implied incremental uranium demand, to 2040

Scenario	**SMR cumulative capacity by 2040 (GW) - assumed**	**Licensing delay (typical FOAK to NOAK scaling)**	**NOAK cost reduction vs FOAK (assumption) ***	**Factory throughput/ manufacturing rate by 2035–2040 (units/yr)**	**Fleet-avg natural-U intensity used #**	**Implied incremental uranium demand from SMRs in 2040 (tU/yr)**
Low (conservative)	0-20	Long; 5-12 years: delayed licensing/slow roll-out (regulatory/ financing bottlenecks)	0-10% NOAK reduction (limited learning)	0-3 units/yr (few factory lines; limited serial production)	150-170 tU/GW/yr	0-3,400
Mid (plausible)	20-60	Moderate; 3-8 years: some streamlining, partial NOAK learning	10-30% NOAK reduction (moderate learning & standardisation)	3-10 units/yr (several production lines; regional factories)	150-170 tU/GW/yr	3,000-10,200
High (accelerated / IEA-like)	60-120 (High-end for IEA, 10% by 2040, depending on global fleet)	Short; 1-4 years: rapid licensing harmonisation, aggressive policy support	25-50% NOAK reduction (strong mass production; aggressive cost learning)	10-40 units/yr (high factory throughput; industrialised supply chains)	150-170 tU/GW/yr	9,000-20,400

*FOAK to NOAK licensing delay refers to the effective time from first-of-a-kind prototype operation to widespread n^{th}-of-a-kind serial deployment at scale.
#Fleet-average natural-U intensity is shown as a small band (150-170 tU/GW/yr). For cross-report comparability, we use 160 tU/GW/yr as our central conversion in the manuscript text (NEA/IAEA convention), but the table reports the full 150-170 range to reflect burn-up/tails variability.

Supplementary Note 4: Mining methods and uranium supply potentials

Mining methods are selected according to orebody geometry, grade, and depth:

- *Open-pit mining* is cost-effective for near-surface, large, low-grade deposits but generates substantial waste-rock and tailings volumes requiring engineered containment. Examples include Rössing and Husab (Namibia) [29–31].
- *Underground mining* (Athabasca unconformity deposits) suits deep or high-grade orebodies, reduces surface impact, and demands strict ventilation and dose management [32, 33].
- *In-situ recovery* dominates current production growth for permeable sandstone-hosted deposits, as demonstrated by Kazakhstan's industry leadership [34]. ISR eliminates conventional tailings and surface waste, though it requires verified aquifer isolation and comprehensive post-mining restoration.

Building on these operational considerations, Table S5 summarises the projected name-plate capacities and ramp-up timelines for conventional uranium mines, alongside potential recovery from phosphate-by-product streams. The conventional mine entries reflect planned or announced production capacities, while the phosphate-by-product estimates incorporate modular recovery plants and literature-based upper-bound scenarios. These values provide a basis for scenario modelling and illustrate how both conventional and unconventional sources could contribute to global uranium supply under varying technological, economic, and regulatory conditions. Table S5 therefore serves to contextualise uranium resource accessibility in operational terms, complementing the earlier discussion of ore grades, deposit types, and extraction methods, and highlighting the role of unconventional streams in potential future supply scenarios.

Table S5: Conventional uranium mine capacity and phosphate-by-product uranium recovery potential

Category	**Project/ Region**	**Name-plate capacity/ potential (tU/yr)**	**Ramp-up timeline/ commissioning assumption**	**Remarks**
Conventional mine	McClean North deposit (Saskatchewan, Canada)	~ 2,000 (starting in 2025)	Commercial production commenced in July 2025, ramping to steady state over 2-3 years [35]	High-grade uranium; pilot scale into production
Conventional mine	Shirondukuyskoye deposit (Siberia, Russia)	~ 2,000 incremental by 2030	First production planned by 2028; assumption of ramp to ~ 2,000 tU/yr by 2030 [36]	Strategic expansion by a vendor-state company
Conventional mine	Global ISR/new mines (aggregate)	~ 30,000 incremental by 2035-2040	Assumption: cumulative new-mine capacity adds ~ 30 ktU/yr by 2035 under favourable investment and permitting. Derived from WNA/agency commentary [37]	Aggregate estimate for model scenarios
Phosphate-by-product recovery	Global phosphate fertiliser plants	4,000-8,000 (pilot/early scale)	Modular recovery plants commissioned 2026-2032; full scale-up to multi-10 k tU/yr by ~2040 under favourable economics, based on IAEA TECDOC and recent studies	Unconventional stream; economics still uncertain [38–40]
Phosphate-by-product recovery	Potential 10-20 % of global demand scenario	~ 10,000-20,000 by around 2045	Assumption: 10-20 % of projected global reactor-demand (~100 k-200 k tU/yr) could be supplied by phosphates under ideal conditions. Use as an upper bound sensitivity	Used for scenario modelling only; not base case [38–40]

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