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The Evolution of Nuclear Energy: Current Capabilities and Future Prospects

Abstract

The global outlook for nuclear energy has shifted significantly in the last few years, from predominantly unfavourable or dismissive views to strongly favourable and optimistic perspectives, in countries all around the world, both developed and developing. This shift is reflected in the growing support for the declaration to triple nuclear capacity by 2050, first endorsed by 21 countries at COP28, and since expanded to include 38 countries. However, a number of important challenges exist that could delay or hinder nuclear energy's contribution to overall energy and security goals as well as global climate goals.

These include economic competitiveness, supply-chain readiness, fuel cycle and waste management issues, regulatory and institutional capacity, and the need to maintain strong safety, security, and safeguards frameworks. These challenges are especially important as new technologies such as small modular reactors (SMRs) and other advanced reactors are deployed.

This Energy Insight examines the major economic, institutional, and technical factors that will shape the future deployment of nuclear power. It reviews the current status of nuclear technologies and programmes, identifies key issues that may influence the pace and scale of nuclear expansion, and highlights areas where further analysis could support policy and investment decisions. Particular attention is given to issues at the intersection of technology, policy, governance, and markets—areas often less emphasised in technically focused nuclear research programmes. It surveys the key challenges and identifies key questions that merit further attention to address these challenges.

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1. Introduction

This renewed momentum has been consolidated by international developments from COP28 to COP30 and beyond; culminating in a growing coalition of 38 countries (WNA 2026a) committed to triple global nuclear capacity by 2050. Nuclear power has re-emerged as a central pillar in discussions on energy transition, sustainability, and security. Following decades of stagnation due to high costs, safety concerns, and public opposition, recent years have witnessed a marked shift in global attitudes. Interest in expanding nuclear energy is now at its highest level since the early development of the technology, with particular emphasis on small modular reactors (SMRs) and advanced reactor designs.

Despite this renewed momentum, significant challenges remain that could limit or hinder nuclear power's contribution to overall energy and security goals, as well as to reducing greenhouse gas emissions and thus contributing to meeting global climate goals. This paper describes these challenges and identifies key questions that merit further attention.

This Energy Insight is structured as follows. Section 2 examines the principal economic and technical challenges affecting the expansion of nuclear power, including issues related to financing, supply chains, first-of-a-kind (FOAK) risks, and the evolving role of SMRs. Section 3 discusses policy, regulatory, and institutional aspects, including regulatory adaptation for advanced reactor technologies and the potential role of digitalisation and artificial intelligence. Section 3 also reviews safety, security, safeguards, and non-proliferation considerations associated with novel reactor designs and emerging deployment models. Section 4 addresses fuel cycle and radioactive waste management challenges, including geological disposal and emerging fuel-cycle concepts. Section 5 examines cross-cutting institutional issues such as public communication, governance challenges in newcomer countries, and workforce development. Section 6 considers strategic deployment choices facing governments and investors when selecting between SMRs, large reactors, or hybrid approaches. Finally, Section 7 concludes by recapitulating the areas to be addressed to advance nuclear deployment and points to more detailed analyses in progress.

1.1 Global Context: Nuclear Power and the Energy Transition

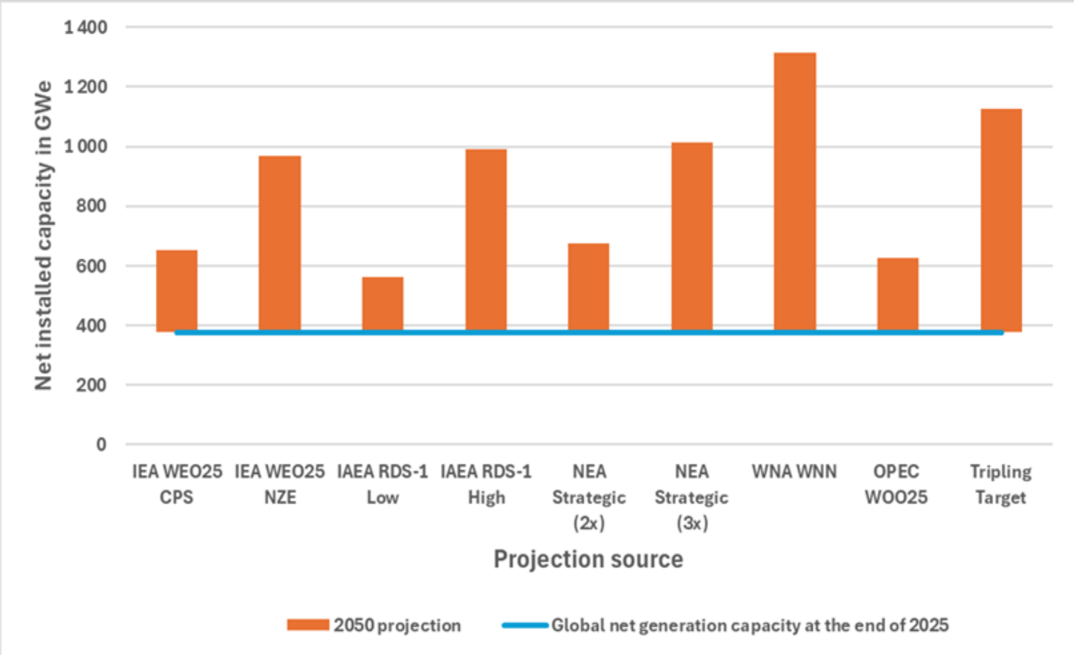
The Climate Action Tracker (CAT 2025) and other analyses confirm that the world is not currently on track to achieve net-zero emissions by 2050. Meeting the Paris Agreement climate goals requires a pragmatic approach that addresses the three prongs of the energy challenge: sustainability, safety and security, and affordability. Nuclear power provides low-carbon, dispatchable electricity that complements renewables and enhances system reliability. This is particularly relevant as electricity demand surges due to the rapid growth of electric vehicles, electrification of industry, proliferation of data centres to support artificial intelligence (AI), and continuing broad growth in electricity usage.

Reflecting this urgency, a series of major international assessments published in 2024–2025 point to a rapidly accelerating interest in large-scale deployment of nuclear power. At the end of 2025, 413 reactors were operating worldwide with a combined capacity of 377 GW(e), providing nearly 10% of global electricity. Over 70% of reactors are in advanced economies, but have an average age exceeding 36 years, necessitating major investments in lifetime extensions.

The IAEA's latest long-term projections show a substantial upward revision in global nuclear capacity, with high-case scenarios now approaching a near-tripling of installed capacity by 2050 (IAEA 2025a). The International Energy Agency's January 2025 report (IEA 2025a) similarly identifies nuclear power as entering a "new era" and calls for a rapid expansion of nuclear capacity to support both decarbonisation and energy security objectives In parallel, the OECD Nuclear Energy Agency has highlighted, through its 2025 "Roadmaps to New Nuclear" initiative, the growing policy momentum and investment interest in fast-tracking new nuclear programmes across both advanced and newcomer countries (NEA 2025a).

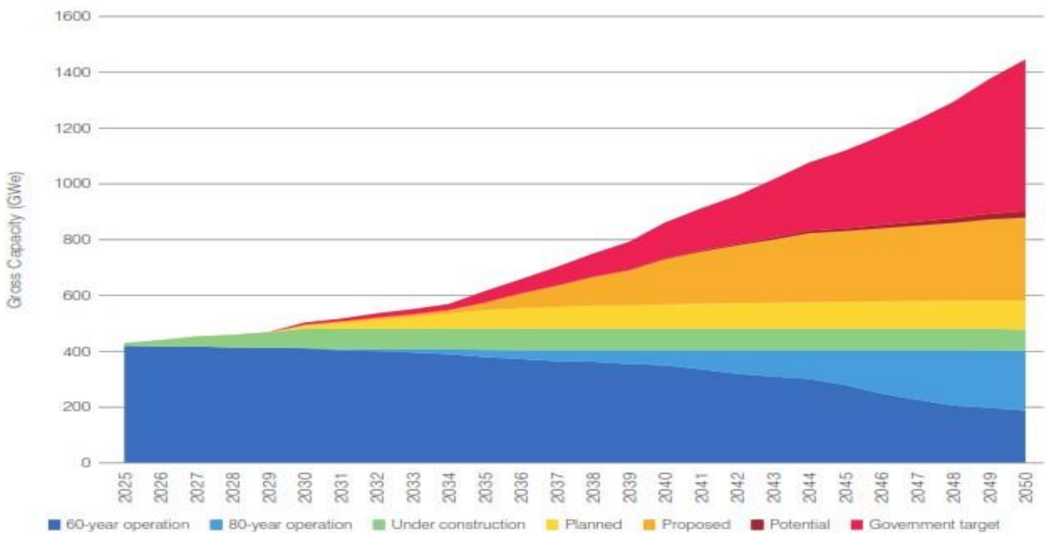
Projections of nuclear power's potential contribution worldwide, from these and other organisations, vary widely, of course, because there are many factors that enter into making such a projection. This wide variance is clearly illustrated in Figure 1, which presents nuclear power capacity projections under multiple scenarios developed by different organisations. The figure highlights a substantial divergence in projections—ranging up to a doubling, tripling and beyond of global nuclear capacity by 2050. Figure 2 shows one example of specific deployment assumptions affecting such projections. The scope of this paper does not allow for a detailed evaluation of the many projections; its principal emphasis is to discuss the economic, technical and societal issues that could affect the potential growth rate of new nuclear power.

Figure 1: Net nuclear generating capacity projections for 2050 in GWe by various organizations for 2050



Sources: IEA WEO25 (IEA 2025b), IAEA-RDS 1 (IAEA 2025a), NEA (NEA 2025a), WNA WNN (WNA 2026c), OPEC WOO25 (OPEC 2025)
Note: Source data harmonised to net capacities

Figure 2: Global nuclear capacity 2025-2050 (GWe gross)



Source: (WNA 2026b)

1.2 Opportunities and Drivers of Nuclear Expansion

Several converging factors underpin the renewed momentum for nuclear power:

- Rising electricity demand, especially for industry, electric vehicles, and AI/data centres, but also due simply to overall growth in developing economies.
- Growing concerns about energy security in light of geopolitical disruptions.
- Recognition of nuclear power's environmental and health benefits compared to fossil fuels.
- Recognition of the problems of implementing a stable electricity grid system based mainly on renewables.
- Increasing financing and partnership opportunities, including technology companies investing in nuclear-linked power purchase agreements.
- Specific advantages of SMRs, including improved safety, modular deployment that reduces initial capital costs and thus assists in the financing, and suitability for small grids or industrial applications.
- Public recognition of the points above and acknowledgement that these are valid drivers for increasing nuclear energy.
- Nuclear as a pillar of the Clean Energy Transition: dispatchable, low-emissions source that complements intermittent renewables.

In any discussion of the future of nuclear power, one needs to recognise that a major shift in emphasis has occurred in the last decade. Whereas the operating reactors worldwide today are almost all what the industry terms "large reactors", characterised by electricity outputs in the range between 600 MWe and 1400 MWe, the development of new Advanced Nuclear Power Reactor (ANPR) designs worldwide has in recent years been heavily toward SMRs. The adjective "modular" is intended to describe a fabrication and deployment scheme in which the key components for a reactor are produced in series in a factory environment and assembled on-site to construct an SMR. Several of these smaller reactor units can be used together to generate the equivalent electric power levels that today are generated by a single large unit. Although the nuclear industry worldwide is also both developing and deploying some new large ANPRs, the SMR emphasis is manifested by the existence of over 100 SMR-development efforts today (NEA 2025c).

Another significant shift relates to market leadership and construction trends, with dominance increasingly moving toward China and Russia, which now account for the majority of reactors currently under construction.

1.3 Nuclear Expansion Options

There are three principal strategies for expanding the market share of nuclear energy, each serving different markets with distinct investment and supply chain implications.

First is to extend the licences of existing reactors through Long-Term Operation (LTO). This low-cost way to maintain current nuclear generation relies on existing nuclear power plants (EPRI 2024; IAEA 2018). It faces less public opposition and is often favourably viewed by the communities hosting the reactors. However, LTO only maintains or slightly increases generating capacity (even if all currently operating reactors are subjected to LTO).

Second, is the construction of new large reactors (LRs). New build LRs incur high initial capital costs that are difficult to finance, take a long time to implement, face regulatory challenges and are subject to uncertain public support. These challenges have resulted in delays and budget overruns in the United States and Europe (Vogtle (US), Hinkley Point C (UK), Olkiluoto (SF) and Flamanville (F)). However, vendors from China, Russia and South Korea have a better track record of completing projects on time and within budget due to their continuous construction projects (IAEA 2024a; NEA 2020; WNA 2025). Domestic nuclear projects that are few and far between suffer from knowledge depreciation throughout the nuclear ecosystem and thus resemble first-of-a-kind (FOAK) undertakings.

Third is to deploy SMRs, which range in size from 20 to 300+ MWe, offer innovative features, promise enhanced operating safety as well as flexibility by providing electricity and non-electric services (e.g., district heat or process heat for high-temperature heat applications). As a nascent technology, SMRs have yet to be deployed in a competitive market setting. Also, most SMR vendors have no prior construction experience. Although the total capital outlay per reactor is lower and therefore easier to finance, the SMR FOAK cost per kW is expected to be significantly higher than that of an LR (IEF 2024; Daigle et al. 2024; Josephs et al. 2025).

As noted above, the nuclear industry worldwide is advancing efforts to develop and deploy several new advanced large reactors as well as many SMR designs. But the outlook remains uncertain. It is unclear how many SMRs will ultimately be deployed over the next two decades or how many advanced large reactors will be deployed.

The attributes of the two categories are in many ways very different. The table below is intended to capture those differences in a way that supports the specific topics addressed in the subsequent text.

Attribute	Small Modular Reactors (SMRs)	Large Advanced Nuclear Power Reactors (ANPRs)
Economics	Lower upfront capital per reactor but at least initially higher capital costs per kWe; FOAK risk; modular economies of multiples	Economies of scale; high capital costs; long implementation timelines; established supply chains,
Safety	Enhanced passive safety, lower probabilities of accidents, smaller inventories, lower accident consequences	Robust but more complex systems; larger accident footprint
Security	Potential vulnerability if deployed at numerous remote sites	Consolidated sites with established protocols
Safeguards and Proliferation	Some designs require HALEU; potential proliferation concerns	Established safeguards for LEU fuels
Waste Management	Smaller but more diverse waste streams; limited back-end planning	Larger but well-characterised waste streams; existing geological disposal planning

The challenge for any given national programme is to identify the optimal mix of LTO, new LRs, and SMRs for rapid nuclear expansion, considering how each interacts with evolving energy systems and storage needs.

1.4 Challenges to Nuclear Expansion

Despite the brighter outlook, significant challenges must be addressed:

- Economics: Concerns include high capital costs, FOAK risks, and uncertainties about whether the "economies of multiples" for SMRs will be realised. Ensuring cost competitiveness requires demonstration projects and financing support. It is unthinkable that the numerous SMR designs being put forward can all be commercialised and enthusiasm of investors may falter as companies fail with their designs and drop out.
- Safety: Although all modern reactors including SMRs incorporate enhanced safety features, challenges to address public confidence remain; issues include robust regulation, transparent communication, and proven operational performance.
- Security: Widespread deployment in diverse siting environments raises security concerns, including potential sabotage or misuse of materials, particularly in newcomer states.

- Safeguards and Proliferation: Advanced designs that use fuels with higher U235 enrichments than today's large reactors or involve reprocessing increase proliferation risks which must be addressed through strong international safeguards.
- Fuel Cycle and Back-End Management: Long-term solutions for spent fuel and high-level waste remain a critical challenge. Many SMR vendors have given insufficient attention to back-end issues, and newcomer countries face prohibitive costs for geological disposal unless shared or take-back solutions are implemented.
- Fuel Security: Ensuring the availability of nuclear fuel presents several challenges. Although there is adequate raw uranium on a world-wide basis, developing the resource and assuring its universal availability may be a challenge. Also, assuring adequate enrichment capacity worldwide to support major growth will require investments that can take many years to materialise, and this could be aggravated if many of the new reactors require so called High Assay Low Enriched Uranium (HALEU) which is enriched to 19-20% instead of the 5% range used in the vast majority of today's operating reactors.
- Supply chain and workforce development: The availability of enough manufacturers of nuclear-specific equipment could be a major bottleneck to rapid expansion. The availability of the many tens of thousands of new workers needed to staff a major expansion will require a worldwide commitment to expanding both higher-education and technician-level training programs.

2. Expanding Nuclear Energy: Economics and Financing Challenges

2.1 Established past approaches perceived as high economic risks

Historically, the push for ever larger nuclear power plants was driven by economies of scale, whereby costs per unit of capacity (kW) decreased as plant size increased. SMRs challenge this approach by pursuing 'economies of multiples' — cost reduction and learning through the serial production of standardised designs in a factory setting. Some of the SMR designs also offer a simpler design than today's LRs, which is projected to save on the capital cost.

A key question is whether these approaches can complement each other. France's attempt in the 1980s and 1990s to combine scaling and multiples by building an extended series of LRs with the same design, was, for instance, hindered by a combination of external events. These include macroeconomic shifts following the collapse in the international oil price, which caused drops in electricity demand and slowed the need for, and rate of, new builds; domestic political changes, which resulted in delayed and inconsistent project approvals; organisational restructuring within the domestic nuclear industry (which led to increased outsourcing, knowledge loss and re-engineering rather than repetition); and post-Three Mile Island and post-Chernobyl regulatory changes (which caused construction delays and expensive design modifications). These events interrupted the rhythm of standardised construction programmes and hindered the learning process (Lovering et al. 2016). One study claimed that this resulted in 'negative learning' (Grubler 2010). In contrast, South Korea's construction of four APR-1400 reactors at Barakah, United Arab Emirates, demonstrated clear learning effects, reducing the cost and construction time for subsequent units (Dalton 2024; Emblemsvåg 2024).

Ultimately, rather than being seen as competing forces, economies of scale and multiples should be viewed as complementary forces that can be integrated over time to make nuclear power more cost-effective (Hanna et al. 2024) . Today, several countries are implementing or planning further LRs, many have aggressive SMR development programmes, and some are pursuing all three options for expanding nuclear power.

2.2 First-of-a-Kind (FOAK) risk mitigation

FOAK implementation and cost hurdles affect almost all innovative technologies and cannot be ignored. Substantial private-sector investment is required for SMR design and development, and the FOAK hurdle will prevent the commercialisation of most of the many designs currently in development, leaving the majority in the 'valley of death' (Frazer-Nash 2025). This occurs when market demand is insufficient for all designs to be produced in the quantities and pace needed to achieve economies of multiples. A key factor in generating adequate demand for early units is securing multiple orders from individual customers. Decision-makers in several countries are considering placing multiple orders for SMRs to strengthen their electricity systems in a cost-effective and sustainable manner. Of particular interest are energy-intensive data centres, which require secure 24/7 power and have the financial capacity to commit to multiple units of a single SMR design, serving as early anchor customers (Basu 2025).

There are also Supply chain issues. Assuming orders are in the pipeline, supply chain readiness and limitations determine how quickly FOAK costs can decline via learning and multiple effects. Conversely, the spacing of orders for the same design affects the willingness of supply chain investors to invest. This is a classic chicken and egg dilemma which is independent of a specific reactor design.

2.3 Energy Security, System Value, and Emerging Market Opportunities

Electricity supply options were traditionally ranked by levelised cost of electricity (LCOE), comparing per-kWh generation costs using largely fixed lifetime parameters. In this framework, demand was treated as external, with consumers as price takers and utilities setting prices through periodic reviews. System costs were less dependent on the type of generation and therefore did not affect rankings. Today, however, wholesale energy costs, which vary sharply by time of day and season, are more relevant than average LCOE (Tareen and Quoilin 2025).

Different generating technologies influence these costs in distinct ways, and the growing share of intermittent generation in many jurisdictions amplifies the challenge of providing reliable 24/7 electricity.

Not only do different generating technologies affect the wholesale energy costs differently, but the growing share of intermittent forms of generation in many jurisdictions amplifies the challenge of providing reliable 24/7 electricity. Reliable systems now require dispatchable generation, demand-side management, and storage, all assessed at the full-system level where some residual risk is unavoidable. Certain customers, such as grid operators, pay premiums for guaranteed 24/7 reliability. Electricity-intensive users like data centres and high-tech firms often take it a step further by installing redundant behind-the-meter generation systems and selling any surplus electricity to the grid (Tozzi 2025).

In terms of applications and markets, SMRs are well positioned to meet a variety of energy needs. While the generation of on-grid electricity remains a key global market, there is growing interest in diverse, disruptive applications, particularly in areas that are otherwise difficult to decarbonise. These include reliable off-grid electricity and heat for remote areas such as mining operations; high-temperature heat for heavy industries like chemical and fertiliser production; hydrogen production; desalination; or marine propulsion to replace carbon-intensive bunker fuels. Several of these energy services can be generated through cogeneration (IAEA 2024c).

2.4 Financing SMRs

Large reactors are highly capital-intensive, costing (depending on size) between $7 and 16 billion per plant in North America and Europe (latest reports suggest considerably higher estimates for the plants under construction in the UK (Fingleton 2025)). In countries that have constructed few or no LRs over the past decades, these costs resemble FOAK conditions. In contrast, countries with continuous construction experience, such as China, Russia and the Republic of Korea, have achieved lower construction costs both domestically and in export markets. Nuclear projects typically use high leverage, with up to 80% of costs supported by sovereign guarantees or export credit agencies. Traditional financing approaches include corporate balance sheet financing used by large vertically integrated utilities with the financial strength to fund projects internally, and direct and indirect government support or any combination thereof.

Newer financing models aim to provide price certainty and enable the recovery of capital costs over extended periods. These include public–private partnerships (PPP), contracts for difference (CfD), regulated asset base (RAB) models, and bilateral state agreements that provide loans, guarantees, or turnkey project delivery. CfDs offer long-term price stability by guaranteeing a fixed price or price range for electricity, shielding investors from market volatility. PPPs are long-term contractual arrangements between government entities and private-sector firms to finance, build, and operate public infrastructure. The RAB model allows investors to earn a return during the construction phase by raising tariffs, thereby lowering the overall cost of capital through reduced interest payments.

SMRs with outputs of 20–300 MWe require lower upfront capital and allow modular, incremental financing. Their smaller size enables combinations of public credit support, private equity, and institutional finance. Early SMR projects are often using government–industry cost-sharing. Some customers opt for vendor-financed or build-own-operate (BOO) models, in which vendors fund construction and operate the plant until they have recovered their investment through long-term energy sales. Developing countries frequently rely on turnkey delivery, with vendors assuming design and execution risk; China and Russia often use turnkey structures for export projects. To date, the SMR finance arrangements appear to predominantly support a design that can overcome the financial FOAK hurdle. While most of the funds involved are rough estimates, the capital exposure per kWe is substantially higher than that of the N^{th} unit of a LR. The SMR philosophy should reduce costs as more units are completed (NEA 2021a).

3. Regulatory and Technical Challenges in Reactor Deployment

3.1 Policy and Regulation

The regulation of nuclear power plants is a mature discipline in essentially all jurisdictions with operating nuclear power plants; however emerging technologies — like many SMRs and novel coolant/fuel cycles, in general — pose new oversight challenges. Effective regulatory oversight ensures that licensees maintain responsibilities for safety, quality assurance, and contractor/sub-contractor oversight (NEA 2025b).

Several key regulatory practices have been broadly accepted:

- A risk-informed, performance-based regulatory framework, which focuses inspection and oversight on activities with greatest safety significance. For example, the U.S. Nuclear Regulatory Commission (NRC) “Reactor Oversight Process” emphasises inspections where potential risks are highest (USNRC, n.d.).
- The regulator retains ultimate responsibility for oversight of contractors, even when the licensee outsources many functions. The licensee must remain the “design authority” and retain core competences.
- Use of internationally recognised standards and guidance (e.g., International Atomic Energy Agency (IAEA) Safety Standards and ISO standards) and peer exchange among regulators (IAEA, n.d., 2025b).

With the emergence of SMRs, modular fabrication, digital instrumentation & control (I&C), and global supply chains, regulatory oversight must adapt to new domains. New or expanded capabilities to support regulatory oversight of next-generation nuclear plants cover several different areas. This would include developing of template safety-case frameworks specifically for SMRs and multi-module sites, including shared-systems and common-cause failure treatment. When a site contains several identical or near-identical modules, common-cause failures and shared systems require oversight adjustments (e.g., inspection frequency, qualification of multiple units). It also requires the harmonisation of digital I&C qualification requirements across jurisdictions. This includes methods for software assurance, cybersecurity, patch management, and licensing of upgrades. Concerning digital I&C and software assurance, the increasing use of COTS (commercial off-the-shelf) components, software updates, and digital instrumentation in nuclear plants demands that the regulator assess cybersecurity, software lifecycle, obsolescence, and supply-chain integrity. Regulators must also define metrics for vendor-chain oversight, including key performance indicators, traceability frameworks, and subcontractor audit frequency, to ensure that licensees maintain sufficient competence to oversee complex international supply networks (NEA 2011; IAEA 2016). Capacity-building is critical for newcomer countries, which may initially import regulatory expertise and must benchmark staffing, organisational structures, budgets, training curricula, and inspection plans for modular fleets (IAEA, 2024b). International harmonisation of licensing frameworks would facilitate cross-border SMR deployment. Also reviewing the various approaches to licensing innovation is needed as the shorter timescales expected for implementing SMRs will not be feasible unless the typical multi-year licencing process is shortened. Fortunately, efforts are already underway worldwide to examine how licensing of SMRs can be different.

3.2 Safety, Security, and Non-Proliferation Aspects for Novel Advanced-Reactor Designs

Safety, security, non-proliferation, and safeguards are fundamental considerations for deploying nuclear power and remain just as important for advanced reactor designs as for traditional reactors currently operating worldwide.

The primary goal of reactor safety systems is to reduce both the likelihood and the consequences of accidents that could damage facilities and cause radiological releases affecting workers, nearby populations, property, and the environment. Security systems aim to reduce the risk and impact of intentional harmful acts—such as sabotage or theft of nuclear materials—by individuals or groups seeking to cause disruption or destruction. Non-proliferation programs and safeguards seek to prevent nuclear materials from being diverted either from a reactor or from a fuel-cycle facility for use in nuclear weapons programs by governments or sub-national actors.

Although these systems have generally been implemented successfully since the early use of nuclear energy, rapid technological, economic, and demographic changes can challenge their effectiveness and stability. While safety, security, non-proliferation, and safeguards are distinct issues, they are interconnected. Design features, operational practices, and administrative controls often create synergies among them, and a strong safety approach significantly supports the effectiveness of the other three areas. However, security and non-proliferation also require protection against deliberate actions either by a government or by a sub-national group attempting nuclear proliferation or terrorism.

Comprehensive risk analysis and assessment are essential for all four areas to minimize both the probability and consequences of failures. These assessments must begin during plant design and continue through operation and long-term management of radioactive materials. The process can be complex, particularly for advanced reactor designs due to their novelty and limited operational experience. Examples of challenges include preventing theft of nuclear material for weapons or dirty bombs and mitigating risks such as sabotage or terrorist acts involving intentional radioactive release.

Many proposed advanced reactors—including large ANPRs and SMRs—employ technologies and fuel cycles similar to current large light-water reactors (LWRs), while others introduce less-tested approaches such as molten salt, lead-cooled, pebble-bed, fast-neutron gas-cooled, and heat-pipe designs. Certain reactors also utilize more highly enriched uranium, involve on-site or remote fuel reprocessing, or require the secure transport of complete reactor cores. These differences necessitate a careful re-evaluation of existing safety, security, safeguards, and non-proliferation frameworks originally developed for large LWRs, both to ensure their continued effectiveness and to identify modifications where needed.

The safety assessment of advanced large reactors and SMRs must consider the full range of off-normal and accident scenarios that could occur. The deployment of multiple smaller units, sometimes at dispersed sites or integrated into industrial facilities, introduces safety challenges that differ from those associated with single large reactors. The existing security frameworks developed for large nuclear power plants, including both physical protection and cybersecurity, may need to be adapted for advanced reactors, particularly where reactors are deployed at remote sites, industrial locations, or co-located in larger numbers. This may be especially important for maritime applications and transportable or microreactors. Safeguards and non-proliferation considerations are also important for SMRs and ANPRs since some advanced reactor concepts use fuels with higher enrichment levels or different fuel forms, which may require adjustments to safeguards approaches, material accountancy, and inspection regimes.

On the other hand, novel reactor designs offer an opportunity to integrate “safeguards by design” from the earliest stages, embedding protective features directly into the reactor concept—something that older LWRs, connected to the grid decades ago, often incorporated only later.

For each of these areas, two central questions must be addressed: whether the current approaches remain adequate for new technologies, and, if not, what adjustments are required to manage emerging risks effectively. Fortunately, a worldwide coordinated effort to tackle all of these issues is under way now among government-sponsored and private research institutes, the reactor developers, and the regulatory agencies in many of the major countries.

3.3 The Roles of Artificial Intelligence

AI has the potential to support the nuclear energy industry throughout the entire lifecycle of nuclear infrastructure as well as in regulatory activities. Nuclear energy systems are highly complex, data-intensive structures. The volume of documentation, reviews, verifications and performance assessments is constantly growing. AI can process and analyse vast amounts of data at speeds far beyond human capability. AI and nuclear energy systems therefore appear to be a promising partnership, enhancing (although not replacing) traditional engineering, planning and safety activities from the initial design stage to decommissioning. AI can model and simulate new reactor designs, assist in performing safety analyses, and support the management of nuclear infrastructure deployment. AI-enabled digital twins can allow engineers and operators to be more effective and efficient as they simulate plant behaviour, test off-normal scenarios, and enhance training. During construction, AI can identify cost and schedule risks, improve quality assurance through computer vision-based inspection of welds and structures, and optimise the setup of complex nuclear supply chains – all of which reduce costs and timelines.

During operations, AI can be used for predictive maintenance and real-time anomaly detection by analysing large volumes of sensor data. This can improve reliability and can reduce unplanned outages while ensuring that humans remain in control of safety-critical decisions. AI can also assist in optimising load following by coordinating with renewable generation and storage, as well as in market forecasting and optimising revenue. Throughout the fuel cycle, AI can enhance fuel performance, optimise reload strategies, and strengthen safeguards and material accounting via pattern recognition (IAEA 2026). In safety regulation, AI can assist in similar ways, but with an additional emphasis on using AI’s extraordinary abilities to digest and search safety data bases and to assimilate complex operational data, although under human guidance.

While the benefits of the AI-nuclear partnership appear plentiful, there are also new risks to consider. AI models need to be trained. Poor quality, incomplete or biased data, or inadequate validation can lead to inaccurate predictions or decisions with potentially severe consequences. Additionally, AI can venture beyond its training data and behave unpredictably. Increased AI integration increases the risk of cyber threats, which could compromise the machine learning process or safety systems. Excessive reliance on AI may result in the degradation of human skills and situational awareness, particularly during rare or extreme events where human judgment is critical.

As AI advances and is increasingly applied to complex systems, the output of AI systems is becoming more and more difficult to interpret, even for the creator of an algorithm, and it is becoming nearly impossible to understand how the AI algorithm arrived at a result. Explainable AI (XAI), which embraces transparency, explainability, interpretability and accountability, has the potential to mitigate this issue by making AI decision-making processes and results traceable and comprehensible. Although human-in-the-loop control is mandatory for safety-related decisions — i.e. because final accountability must always rest with a human — AI integration with nuclear energy systems can provide major benefits in terms of operational efficiency and safety throughout the system.

In light of the above, use of AI should be preceded by careful evaluation of the potential benefits and limitations of the use of AI applications across each aspect of a nuclear plant’s lifecycle, including design, construction, operations, maintenance, and decommissioning. It is also important that in AI-assisted nuclear operations, there is constant attention to safety through validation, based on human oversight. Finally, there is a need, industry-wide and world-wide, to develop governance, explainability, and cybersecurity frameworks for AI in all nuclear activities. As part of this, there needs to be a focus on establishing governance models that define accountability and legal boundaries for AI usage.

4. Fuel Cycle and Radioactive Waste Management

The management of spent fuel and radioactive waste remains one of the most persistent challenges facing nuclear power. Although technical concepts for long-term disposal have been studied for several decades, implementation has proven slow and politically complex. The emergence of new reactor concepts, particularly SMRs, introduces additional uncertainties related to fuel cycles, waste streams, and disposal strategies.

4.1 Development of the Geological Disposal Concept

Very early, experts agreed that the spent fuel itself, or highly radioactive wastes produced by processing the spent fuel, could be safely disposed of in deep geological formations that have been stable for millions of years (NAS 1957). This concept was subsequently developed, with detailed designs being studied for deep geological repositories (DGR) which use a combination of engineered and geological barriers to isolate disposed wastes from the human environment for the very long times needed for their radioactivity to decay sufficiently.

The original justification was based on the recognition that the future evolution of a DGR could be assessed only if the environment in which it is constructed is stable over the very long times for which the wastes remain a hazard. This implied that scientists believed they were capable of assessing the evolution of such formations over times up to at least 100,000 years. Although geologists routinely study formations that are very much older up to 100's of millions of years, no other technological challenges had until then looked explicitly at such timescales. More recently, climate scientists have extended greatly the time horizons of their assessments – but in a more dynamic surface environment.

Experts in deep geological disposal developed technical concepts combining engineered and natural safety barriers, along with safety assessment methodologies that produced quantitative estimates of potential releases from DGRs under a wide range of scenarios. Nevertheless, many scientists and members of the public expressed scepticism about the robustness of these estimates. The nuclear community largely responded defensively rather than proactively, as exemplified by a series of "Collective Opinions" issued by experts from the NEA and IAEA: in 1985, asserting that long-term isolation of high-level waste or spent fuel would meet relevant safety objectives (NEA, 1985); in 1991, claiming that experts understood how to analyse long-term safety (NEA, 1991); and in 1995, affirming that deep geological disposal is ethically and environmentally justified (NEA, 1994, 1995). In hindsight, it is clear that presenting this sequence of opinions in a different order might have been more effective.

Debate continues on some of the technical, ethical, societal and philosophical tenets underlying the concept of deep geological disposal, with interesting questions being revisited. Are the current generations compelled to implement DGRs soon to satisfy intergenerational equity requirements or can the wastes be stored for centuries at the surface? Do the large sums of money spent today on DGR related work properly reflect intragenerational equity concerns? Do discussions of timescales of 100s of thousands of years help or hinder public understanding? Are the very strict safety criteria (e.g. maximal allowable doses of 0.1mSv/y) justifiable? How do they compare with other risk criteria?

4.2 The Current Status of Geological Disposal

Long-term solutions for spent fuel and high-level waste remain a critical challenge. Many potential vendors of new SMRs have given insufficient attention to back-end issues, and newcomer countries face prohibitive costs for geological disposal unless shared or take-back solutions are implemented. From the very beginning of nuclear power, there has been a tendency in the expert nuclear community to underestimate the technical challenges – and even more so the societal challenges – of developing and implementing the technologies needed for short and long-term management and disposal of radioactive wastes.

There are some pragmatic reasons for this postponement of repository implementation. Because the spent fuel must be cooled at the surface for some decades before disposal underground and because the facilities needed for this storage are cheaper and simpler than a deep repository, work on the implementation of technologies needed at the backend of the fuel cycle was not a high priority. In practice, however, lack of public and political acceptance of DGR projects has had a greater impact on blocking progress to implementation. Today, the required elements for an accepted DGR solution appear to be confidence in the operational and long-term safety (involving a complex analysis of the long-term future behaviour), agreement on a specific site, engineering competence for construction, and assurance of adequate funding. A few countries—including Finland, Sweden, and France—have largely overcome these hurdles and are close to constructing deep geological repositories. Many other countries, however, have had major setbacks in their disposal programmes and today have only far future visions for the implementation of these very expensive facilities. Examples are 2065 in Czechia, 2050 in Germany, 2070 in Spain, 2130 in the Netherlands and 2075 in the UK; other nations, including the USA have no projected dates at all.

4.3 Back-End Challenges for SMR Deployment

There are immediate backend issues affecting the potential growth of nuclear power. As in the original rise of nuclear power in the 1970s, issues associated with management of radioactive wastes have been somewhat neglected in the current wave of nuclear-power enthusiasm. Almost none of the over 70 plus designs put forward for SMRs has made important reference to management of the wastes (NEA 2025c). Subsequently, some potential developers have begun to address the issue, sometimes with optimistic assessments of the feasibility of reducing, or even eliminating, some of the most problematic long-lived wastes.

For designs based on the current light water reactor fuel cycle, adaptation of existing waste management processing and disposal concepts may be relatively straightforward. Even for these, however, the handling, packaging and disposal techniques need to be studied. For the more exotic new fuel cycles, in particular molten salt reactors, original challenges are to be faced. In any case, in some of the future global nuclear power scenarios that are being put forward, radioactive wastes may be produced in diverse forms at numerous dispersed locations around the world and these will have to be safely and securely managed. Much work that needs to be done on SMR fuel cycle and waste management issues is of a highly technical nature, but, given the recurring public and political debate on the long term challenges involved, strategic issues are also important. An example of a technical challenge with a strong societal component is defining a siting strategy for the new SMRs, in countries with existing large reactors (e.g. sharing the same site) or in newcomer nuclear countries (possibly at remote sites).

4.4 The viability of multinational repositories

A multinational repository (MNR) is a disposal facility in one country which is prepared to accept radioactive waste generated in another country. MNR models can cover shared facilities initiated through partnership between various nations, or by a commercial service provider. As has been demonstrated over the past decades, national DGR programmes are difficult to implement and costly, hence an opportunity to avoid or share this burden could be welcome to any country responsible for such waste. The high expectations for SMRs, if fulfilled, may also lead to small NPPs with wider geographical distribution in a range of countries. MNR concepts may then be even more relevant. Future developments may include commercial initiatives by disposal service providers or offers by SMR supplier nations to take back fuel or even complete reactor cores. The technical implications of accepting SMR SNF into an existing disposal programme are mostly the same for either a national DGR or an MNR (Kinghorn-Mills et al. 2025). Should multiple potential MNR users be interested in a particular SMR, technology, it might ease the decision to deploy SMRs if a common disposal solution is being investigated.

5. Institutional and Cross-cutting Issues

5.1 Communication of Risks and Benefits

Effective risk communication is essential for sustaining public trust, securing political support, and ensuring the long-term stability of nuclear programmes. This is especially important as new nuclear projects, particularly new technologies or first-of-a-kind deployments of SMRs and large ANPRs, introduce systems with limited operational history, unconventional siting patterns, and new industrial applications (NEA 2021a).

According to the Nuclear Energy Agency (NEA), such projects often face heightened public scrutiny, emotional responses, and information asymmetries. Public unfamiliarity, amplified by social media ecosystems and AI-generated misinformation, raises the risk of misunderstanding and organised opposition (NEA 2010). In newcomer countries, communication challenges are further compounded by limited institutional experience and lower baseline knowledge of nuclear technologies. Careful study of the evolving media landscape is therefore required to ensure that risk communication enables, rather than obstructs, the deployment of emerging nuclear systems (IAEA 2022).

The NEA emphasizes that risk communication must be interactive, trusted, and responsive to stakeholder concerns rather than one-way information dissemination. Empirical research finds that risk perceptions of nuclear power are strongly correlated with factors such as trust in institutions, perceived benefit, past experience with nuclear accidents, and geographic proximity to plants. The social amplification of risk framework demonstrates that the way risk information is transmitted and mediated can amplify or attenuate public responses beyond technical hazard magnitude, particularly in contexts characterised by low institutional trust and high information asymmetry (NEA 2021b).

Novel nuclear reactor designs, such as SMRs, molten-salt reactors, fast-spectrum “breeder” reactors, and reactors using new fuel cycles, present specific communication challenges. Public unfamiliarity with these technologies—due to limited operating experience—can lead to low trust and increased susceptibility to misperception or opposition. The introduction of complex hazards, such as molten salt chemistry, lead-coolant systems, or sodium fires, requires careful translation into non-technical language without oversimplifying or causing undue alarm. Multi-purpose plants that integrate nuclear power with desalination, hydrogen production, or industrial heat offer benefits beyond traditional electricity, which may be less apparent to the general public. At the same time, the evolving media landscape, including social media and AI-generated content, necessitates proactive strategies to disseminate verifiable scientific and technical information, counter misinformation, and maintain credibility (NEA, 2010).

Initiatives to improve communication in nuclear energy contexts could include several complementary approaches. Comparative assessments of public perception and communication effectiveness across different national contexts—contrasting countries with established nuclear programmes and those without—can enhance understanding of how trust, benefit–risk perception, and message effectiveness vary (NEA, 2010). Tailored communication strategies for novel nuclear applications, such as desalination, hydrogen production, industrial heat, maritime deployment, and dedicated power supply for data centres, should incorporate benefit framing, fairness considerations, and contextual relevance (IAEA, 2024c). The evaluation and deployment of interactive digital tools, including AI-supported transparency mechanisms, real-time monitoring dashboards, and social-media engagement platforms, are increasingly important for fostering public trust (NEA, 2025a). Finally, assessing communication effectiveness requires accurate and meaningful metrics that capture shifts in perceived trust, knowledge, acceptance, and resilience to misinformation, as well as the success of corrective actions during high-attention events (IAEA, 2020a).

5.2 Deployment in Newcomer Countries: Institutional, Regulatory, and Infrastructure Challenges

The anticipated global expansion of nuclear power—particularly through SMRs and large ANPRs—will increasingly involve newcomer countries with limited institutional, regulatory, and technical experience. Unlike established nuclear countries, newcomer states must build much of their institutional architecture from scratch, often in parallel with vendor negotiations and construction activities (IAEA 2024b).

Moreover, the modularity and siting flexibility of SMRs enable more distributed and sometimes remotely sited reactor fleets, potentially across multiple regions or industrial sites (NEA 2021a). This raises new challenges related to inspection frequency, safeguards implementation, fuel transport logistics, emergency preparedness, and transboundary risk communication. Governance and sovereignty concerns also arise when foreign vendors operate facilities under BOO or state-to-state arrangements.

Also, newcomer states face steep challenges in building regulatory organisations capable of overseeing multiple reactors or modular deployments. SMRs deployed in clusters or dispersed locations require adapted inspection strategies and new regulatory competencies (IAEA 2024b; NEA 2021a). They also must establish modern nuclear laws, liability regimes, emergency-management systems, cybersecurity requirements, and physical-protection frameworks (Stoiber et al. 2010). Reliance on foreign fabrication and limited domestic manufacturing capacity introduces vulnerabilities in fuel supply, component delivery, and quality assurance (NEA 2021a). These risks face many nations intending to increase their nuclear energy production, but they are especially challenging for nuclear newcomers.

Increasingly, newcomer states may rely on BOO, build-own-operate-transfer (BOOT) or public-private-partnership (PPP) contractual arrangements for financing nuclear infrastructure projects. These all raise important questions regarding sovereignty, long-term contractual obligations, and control over safety-critical decisions (NEA 2021a). Such arrangements can blur traditional boundaries between regulator, operator, and vendor, particularly when foreign entities retain long-term operational control.

Regional cooperation can reduce costs and accelerate readiness by pooling regulatory expertise, inspection resources, and fuel-cycle services. Shared approaches may include joint training programmes, common regulatory standards, regional waste-management solutions, and coordinated emergency preparedness frameworks. Reactor sites located near national borders require enhanced coordination between neighbouring states, particularly for emergency preparedness, information-sharing, and joint response planning (IAEA 2015).

Finally, a shortage of skilled personnel remains a major barrier for many newcomer countries. Sustainable nuclear deployment requires long-term planning for education, training, and knowledge retention across regulatory, operational, cybersecurity, and emergency-response domains (IAEA 2011).

6. Strategic Deployment Decisions for SMRs and large ANPRs

Countries, utilities, and private actors face complex decisions regarding whether to deploy SMRs, large ANPRs, or hybrid combinations (Davis 2022). These decisions depend on cost trajectories, supply-chain maturity, technology readiness, siting flexibility, workforce availability, emissions-reduction objectives, and financing capacity. Private-sector actors, particularly data-centre operators and large industrial consumers, are already influencing deployment pathways through early technology selection and power-purchase agreements (IEA 2023). Strategic planning therefore requires transparent, technology-neutral decision frameworks capable of comparing deployment pathways based on system-level impacts, national readiness, and realistic assessments of delivery potential.

Each country's economic structure, industrial base, financial system, and regulatory culture strongly influence nuclear suitability and project viability. Many governments have adopted strategies based on SMRs or large ANPRs, or both, based on different selection criteria reflecting national priorities (often favouring domestic designs), regulatory capacity, and industrial structure. Published examples are from the United Kingdom, Poland, Sweden, and Canada. But large technology companies and industrial users increasingly influence reactor design choices, particularly where firm, low-carbon power is required for data centres and energy-intensive industrial processes. Combining SMRs with large ANPRs or life extension of existing fleets may enhance system flexibility and resilience under different demand and decarbonisation pathways. A concern is that announcements of new SMR and large ANPR projects often appear to exceed what current supply chains, regulatory institutions, and vendor capabilities can deliver (NEA 2025c).

Procurement models strongly influence project risk, cost certainty, and schedule performance. Amongst options being examined today are Engineering, Procurement and Construction (EPC), BOO, BOOT, PPP, and state-to-state arrangements.

7. Conclusions

Nuclear energy has re-emerged as a significant option in global discussions on energy security, electricity system reliability, and decarbonisation. Recent international assessments imply that nuclear capacity will expand substantially by mid-century, although projections vary widely depending on economic conditions, technological progress, and policy choices. As this paper has shown, the key issue is not whether nuclear power can contribute to the energy transition, but under what conditions its deployment can occur at meaningful scale.

Economic factors remain central. Large reactors continue to face very high capital costs and long construction periods, while SMRs must still demonstrate that modular fabrication and serial deployment can deliver the anticipated cost reductions and financial risk mitigation. Supply-chain capacity, access to suitable fuels, and the availability of skilled personnel will also strongly influence the pace at which new projects can move forward.

Institutional and governance frameworks will play an equally decisive role. Licensing systems, regulatory oversight, and public confidence must evolve to accommodate new reactor designs and deployment models while maintaining the high safety, security, and safeguards standards that have long characterised the nuclear sector. These challenges are particularly important for newcomer countries seeking to establish credible regulatory and operational capabilities.

The management of spent fuel and radioactive waste remains one of the most complex long-term challenges for nuclear energy. The emergence of new reactor technologies, particularly SMRs with diverse fuel cycles, may introduce additional waste forms and fuel supply requirements that are not yet fully addressed by existing waste management strategies. Progress will require continued technical and infrastructure development, stable regulatory frameworks, and sustained public and political acceptance.

Taken together, these considerations suggest that the future of nuclear power will depend on the successful alignment of technology, economics, governance, and societal acceptance. Addressing the challenges discussed in this paper will require continued analytical work and targeted studies that examine economic models, regulatory adaptation, supply-chain development, fuel-cycle management, and governance frameworks in greater depth. The authors intend to build on the present analysis in a subsequent paper that will outline possible areas where such studies and research activities could help clarify policy choices and support informed decision-making regarding the future deployment of advanced nuclear technologies.

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