# The Future of Nuclear Energy: Harnessing Technological Advancements and Innovations

The landscape of nuclear energy is rapidly evolving, with emerging technologies poised to transform how we generate, distribute, and integrate nuclear power into our energy systems. Recent developments in small modular reactors, advanced generation systems, and digital integration tools offer promising solutions to longstanding challenges in the nuclear industry. Through comprehensive analysis of current research and development trends, this report reveals how innovations in nuclear technology are addressing critical concerns related to safety, efficiency, cost, and environmental impact. These advancements position nuclear energy as an increasingly viable component of global decarbonization strategies, capable of providing reliable baseload power while supporting the integration of renewable energy sources into modern grids.

## The Evolution of Small Modular Reactors

## Design Principles and Safety Features

Small Modular Reactors (SMRs) represent a significant departure from conventional nuclear plant designs, offering compact, factory-built units that can be transported to installation sites. These reactors are defined as nuclear power plants with an output of up to approximately 300 MWe that incorporate higher safety standards, modularity, and standardized construction processes, enabling more predictable delivery models based on economies of series production[1](https://www.oecd-nea.org/jcms/pl_71126/examining-the-safety-of-small-modular-reactors" \t "https://www.perplexity.ai/search/_blank). The current development landscape is remarkable, with more than 70 distinct SMR concepts under development worldwide, spanning various technological approaches and maturity levels[1](https://www.oecd-nea.org/jcms/pl_71126/examining-the-safety-of-small-modular-reactors" \t "https://www.perplexity.ai/search/_blank). These designs frequently leverage innovative technology and inherent safety features that fundamentally change the risk profile of nuclear generation.

The safety philosophy behind SMRs represents a paradigm shift in nuclear design thinking. Rather than relying solely on active safety systems with multiple redundancies, many SMR designs incorporate passive and inherent safety characteristics that function without operator intervention or external power sources. This approach addresses one of the most significant public concerns regarding nuclear energy by creating systems where the laws of physics naturally prevent or mitigate potential accidents. The international nuclear community is taking these safety innovations seriously, as evidenced by the formation of dedicated research groups like the NEA Committee on the Safety of Nuclear Installations' Expert Group on Small Modular Reactors (EGSMR), which brings together experts from 15 countries to develop scientific foundations supporting safety demonstrations of advanced SMR technologies[1](https://www.oecd-nea.org/jcms/pl_71126/examining-the-safety-of-small-modular-reactors" \t "https://www.perplexity.ai/search/_blank).

## Economic and Deployment Advantages

The economic case for SMRs is built upon several interconnected advantages that address historical challenges with conventional nuclear plants. Traditional gigawatt-scale nuclear facilities have frequently experienced substantial construction delays and cost overruns that have hampered industry growth[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank). In contrast, SMRs offer a different economic model based on smaller initial capital requirements, scalable deployment, and manufacturing efficiencies. By employing existing reactor technology, standardized fuels, and fully modular construction techniques, SMR developers aim to deploy significant baseload capacity within shortened timeframes, potentially bringing new nuclear generation online before 2030[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank).

The scalability aspect of SMRs provides particular value for growing energy demands. With power outputs ranging from 15 MW to 500 MW, different SMR designs can serve various market needs, from distributed generation to grid support[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank). This flexibility enables phased deployment that aligns with incremental demand growth. For instance, data center developers considering nuclear solutions can implement capacity additions that precisely match their expanding energy requirements, adding 60 MW every six months until reaching full operational capacity[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank). This approach drastically reduces the financial risks associated with large upfront investments in oversized generation assets, making nuclear energy accessible to a broader range of potential customers and applications.

## Grid Integration and Applications

SMRs offer unique capabilities for grid integration that extend beyond traditional baseload operation. Their modular nature enables N+1 redundancy configurations, where additional generating capacity ensures uninterrupted power supply even during maintenance or refueling outages[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank). This redundancy is particularly valuable for critical infrastructure and industrial applications with zero-tolerance for power interruptions. For example, a data center with 100 MW load requirements might contract for 140 MW of SMR capacity, exporting excess power to the grid during normal operations while maintaining full operational capability when individual units are offline[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank).

The flexibility of SMRs also creates new opportunities for hybrid energy systems that combine nuclear generation with renewable sources and storage technologies. By providing firm, dispatchable power that complements the intermittent nature of wind and solar generation, SMRs can facilitate higher renewable penetration while maintaining grid stability. Real-world implementations demonstrate the economic viability of this approach, with case studies showing 25-35% cost savings on delivered power compared to grid alternatives, while also reducing carbon emissions by approximately 4 million tonnes over a typical 15-year contract lifetime[2](https://climateaccord.org/wp-content/uploads/2024/08/ICA_Power_Working_Group_Nuclear_Case_Study_072024.pdf" \t "https://www.perplexity.ai/search/_blank). These economic and environmental benefits illustrate why SMRs are increasingly viewed as a critical technology for achieving decarbonization goals without sacrificing reliability or imposing excessive costs on energy consumers.

## Advanced Reactor Technologies

## Generation IV Systems and Design Goals

Generation IV nuclear systems represent a comprehensive reimagining of reactor design principles that aims to overcome limitations in current commercial technologies. These advanced systems are defined by specific performance criteria that go beyond incremental improvements, targeting transformative advances in fuel efficiency, safety, waste management, and proliferation resistance[3](https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/nuclear-what-is-a-4th-generation-reactor/" \t "https://www.perplexity.ai/search/_blank). To be classified as Generation IV, a nuclear system must demonstrate dramatically improved fuel utilization compared to existing plants and incorporate design features that physically prevent severe accidents from resulting in radioactive releases to the environment[3](https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/nuclear-what-is-a-4th-generation-reactor/" \t "https://www.perplexity.ai/search/_blank). Additionally, these systems must use fuel cycles where uranium and plutonium remain mixed with other elements, making weapons proliferation substantially more difficult[3](https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/nuclear-what-is-a-4th-generation-reactor/" \t "https://www.perplexity.ai/search/_blank).

The development of Generation IV technologies reflects a recognition that the global nuclear fleet is aging, with an average plant age of 30 years as of 2020, and approximately 25% of operational reactors exceeding 40 years in service[3](https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/nuclear-what-is-a-4th-generation-reactor/" \t "https://www.perplexity.ai/search/_blank). This aging infrastructure has prompted concurrent efforts to extend existing plant lifespans through long-term investments and safety upgrades implemented after the Fukushima accident, while also advancing next-generation designs. China achieved a significant milestone in this progression by successfully starting up its first fourth-generation reactor in late 2021 with the high-temperature gas-cooled modular pebble bed (HTR-PM) demonstration project[3](https://www.polytechnique-insights.com/en/braincamps/energy/the-latest-technological-advances-in-nuclear-energy/nuclear-what-is-a-4th-generation-reactor/" \t "https://www.perplexity.ai/search/_blank). This achievement illustrates the transition from theoretical designs to practical implementation that is gradually reshaping the nuclear landscape.

## Molten Salt Reactor Innovations

Molten salt reactors (MSRs) represent one of the most promising Generation IV technologies, offering multifaceted advantages through the unique properties of salt-based systems. These reactors utilize salt mixtures—often containing common, inexpensive, and non-toxic components including table salt—as coolants, energy transfer media, and even as the carrier for nuclear fuel[4](https://inl.gov/molten-salt-reactors/how-molten-salt-could-be-the-lifeblood-of-tomorrows-nuclear-energy/" \t "https://www.perplexity.ai/search/_blank). This approach creates fundamental differences in reactor behavior and safety characteristics compared to conventional water-cooled designs, driving increased investment in MSR research and development at facilities like Idaho National Laboratory, which is establishing comprehensive molten salt capabilities including characterization facilities and experimental reactors[4](https://inl.gov/molten-salt-reactors/how-molten-salt-could-be-the-lifeblood-of-tomorrows-nuclear-energy/" \t "https://www.perplexity.ai/search/_blank).

The safety advantages of molten salt systems derive from inherent physical processes that provide passive protection against overheating and power excursions. When molten salt fuel overheats, it naturally expands, reducing the effectiveness of the fission reaction and essentially shutting down the reactor without requiring active intervention[4](https://inl.gov/molten-salt-reactors/how-molten-salt-could-be-the-lifeblood-of-tomorrows-nuclear-energy/" \t "https://www.perplexity.ai/search/_blank). This self-regulating behavior enables the reactor core to automatically adjust its power output to match heat removal requirements, creating natural load-following capabilities that align generation with consumer demand[4](https://inl.gov/molten-salt-reactors/how-molten-salt-could-be-the-lifeblood-of-tomorrows-nuclear-energy/" \t "https://www.perplexity.ai/search/_blank). Furthermore, the liquid state of the fuel at operating temperatures enables continuous introduction of new fuel and removal of waste products during operation, eliminating conventional refueling outages and potentially improving plant availability and economics.

## Thorium Fuel Cycle Potential

Thorium-based nuclear power generation offers a compelling alternative to conventional uranium fuel cycles, with several distinct advantages that could transform nuclear energy production. Thorium is approximately three times more abundant than uranium in the Earth's crust, with concentrations similar to lead and gallium, suggesting a substantially larger fuel resource base[5](https://en.wikipedia.org/wiki/Thorium-based_nuclear_power" \t "https://www.perplexity.ai/search/_blank). When used in nuclear reactors, thorium undergoes neutron capture to form uranium-233, which then serves as the primary fissile material supporting the chain reaction. This thorium-uranium conversion cycle produces significantly reduced quantities of long-lived transuranic elements compared to conventional uranium-plutonium cycles, potentially simplifying waste management challenges[5](https://en.wikipedia.org/wiki/Thorium-based_nuclear_power" \t "https://www.perplexity.ai/search/_blank).

The practical feasibility of thorium fuel cycles has been demonstrated at commercial scale through the Light Water Breeder Reactor (LWBR) core installed at the Shippingport Atomic Power Station. This 60 MWe thorium-powered system operated successfully from 1977 through 1982, generating over 2.1 billion kilowatt-hours of electricity while achieving a breeding ratio of 1.014—effectively producing more fissile material than it consumed[5](https://en.wikipedia.org/wiki/Thorium-based_nuclear_power" \t "https://www.perplexity.ai/search/_blank). Despite a three-decade period of reduced research activity following this demonstration, interest in thorium has resurged among nuclear scientists and policymakers. Advocates, including prominent figures like Ralph W. Moir and Edward Teller, have characterized thorium as potentially providing "a 1000+ year solution or a quality low-carbon bridge to truly sustainable energy sources solving a huge portion of mankind's negative environmental impact"[5](https://en.wikipedia.org/wiki/Thorium-based_nuclear_power" \t "https://www.perplexity.ai/search/_blank). This renewed interest has led to research reactor development and commercial plans for full-scale thorium-based power plants.

## Fusion Energy Prospects

Fusion energy represents the horizon technology in nuclear power development, offering the theoretical prospect of nearly limitless baseload electricity generation with minimal environmental impact. Unlike fission, which splits heavy atoms to release energy, fusion combines light elements to create heavier ones, mimicking the process powering the sun. This approach produces almost no carbon dioxide emissions and generates only small quantities of short-lived radioactive waste, addressing two primary environmental concerns associated with conventional nuclear power[6](https://www.iea.org/news/iea-committee-on-energy-research-and-technology-focuses-on-state-and-prospects-of-nuclear-fusion-at-thematic-workshop" \t "https://www.perplexity.ai/search/_blank). Though fusion technology remains at an early development stage, accelerating research breakthroughs and intensifying government and industry efforts across the United States, Europe, and Asia are gradually bringing this once-distant technology closer to practical implementation[6](https://www.iea.org/news/iea-committee-on-energy-research-and-technology-focuses-on-state-and-prospects-of-nuclear-fusion-at-thematic-workshop" \t "https://www.perplexity.ai/search/_blank).

The global fusion research landscape is characterized by a mix of large multinational experimental projects and smaller private ventures pursuing diverse technical approaches. This research ecosystem benefits from substantial international collaboration, which has become increasingly important given the scale and complexity of fusion development challenges[6](https://www.iea.org/news/iea-committee-on-energy-research-and-technology-focuses-on-state-and-prospects-of-nuclear-fusion-at-thematic-workshop" \t "https://www.perplexity.ai/search/_blank). Organizations like the International Energy Agency (IEA) have supported fusion energy research for many years through Technology Collaboration Programmes (TCPs) that address fundamental research questions, applied engineering challenges, and cross-cutting aspects such as safety[6](https://www.iea.org/news/iea-committee-on-energy-research-and-technology-focuses-on-state-and-prospects-of-nuclear-fusion-at-thematic-workshop" \t "https://www.perplexity.ai/search/_blank). As these efforts progress, governments are exploring more effective policies and funding mechanisms to accelerate development, with particular emphasis on enhancing cooperation between industry and publicly funded research institutions. These collaborative approaches recognize that bringing fusion from laboratory demonstrations to commercial energy production will require coordinated contributions from multiple sectors and disciplines.

## Digital Transformation in Nuclear Energy

## Artificial Intelligence Applications

Artificial intelligence is transforming how nuclear facilities are designed, operated, and maintained, offering solutions to longstanding challenges in this highly regulated industry. The integration of AI technologies enables more sophisticated approaches to safety monitoring, efficiency optimization, and predictive maintenance, potentially reducing operational costs while enhancing reliability. These capabilities are particularly valuable for next-generation reactor designs that incorporate more passive safety features and may operate with reduced on-site staffing compared to conventional plants.

Advanced AI algorithms can continuously analyze thousands of sensor inputs from reactor systems, identifying subtle patterns and anomalies that might escape human detection. This capability creates opportunities for early identification of equipment degradation or operating conditions that could eventually lead to component failures. By detecting these precursors before they progress to actionable problems, maintenance can be scheduled proactively during planned outages rather than responding to unexpected failures. This predictive approach minimizes both maintenance costs and operational disruptions while potentially extending the useful life of critical equipment through more precise condition monitoring and intervention timing.

## Digital Twin Technology

Digital twin technology represents one of the most promising digital innovations for next-generation nuclear systems, particularly for smaller, more distributed designs like microreactors. As explained by Christopher Ritter from Idaho National Laboratory, these digital twins are "living virtual models" that create detailed computational representations of physical assets[7](https://www.aiwire.net/2024/10/10/ai-debrief-digital-twins-and-ai-in-next-gen-nuclear-reactor-operations/" \t "https://www.perplexity.ai/search/_blank). For newer technologies like factory-fabricated microreactors—which can be shipped by rail and deployed in remote locations—digital twins enable new operational approaches including potential remote fleet management with reduced on-site personnel requirements[7](https://www.aiwire.net/2024/10/10/ai-debrief-digital-twins-and-ai-in-next-gen-nuclear-reactor-operations/" \t "https://www.perplexity.ai/search/_blank).

The implementation of digital twins supports the development of near-autonomous operations for distributed nuclear assets, addressing unique challenges associated with these smaller, more numerous systems. Unlike traditional large nuclear facilities with substantial on-site staff, microreactors may operate in locations where maintaining full-time specialized personnel is impractical or prohibitively expensive. Digital twins bridge this gap by providing comprehensive real-time information about reactor conditions, enabling centralized monitoring and control capabilities that support safe and efficient operation with minimal local intervention. This approach represents a fundamental shift in operational philosophy for nuclear systems that has parallels in other industrial sectors but requires particularly sophisticated implementation given the safety requirements and regulatory framework surrounding nuclear technology[7](https://www.aiwire.net/2024/10/10/ai-debrief-digital-twins-and-ai-in-next-gen-nuclear-reactor-operations/" \t "https://www.perplexity.ai/search/_blank).

## Remote Monitoring and Operations

The integration of advanced digital technologies is enabling unprecedented capabilities for remote monitoring and operations in nuclear facilities. These capabilities are particularly relevant for microreactors and other small modular designs intended for deployment in distributed configurations or challenging environments. By implementing comprehensive sensor networks connected through secure communications infrastructure, operators can maintain detailed awareness of system conditions across multiple facilities from centralized control centers, potentially reducing staffing requirements while maintaining or improving safety oversight.

This transition toward remote operations represents a significant evolution in nuclear operating philosophy, requiring careful balance between technological capabilities and human oversight. While automation can handle routine operations and respond to well-characterized conditions, human expertise remains essential for addressing novel situations and making complex judgments. The optimal approach typically involves collaborative human-machine systems where digital technologies handle data collection, analysis, and routine decision-making while trained operators provide strategic oversight and intervention when necessary. This hybrid model leverages the complementary strengths of human and artificial intelligence, potentially creating operations paradigms that are more reliable and resilient than either could achieve independently.

## Climate Imperatives and Nuclear Innovation

## Role in Decarbonization Strategies

Advanced nuclear technologies are increasingly recognized as vital components in comprehensive decarbonization strategies aimed at limiting global temperature increases and mitigating climate change impacts. As highlighted by the Global Nexus Initiative, innovative nuclear designs including smaller, more flexible reactors are growing in importance as the global community confronts the interconnected challenges of reducing carbon emissions, meeting expanding electricity demand, and ensuring the continued peaceful use of nuclear technology[8](https://globalnexusinitiative.org/results/reports/advancing-nuclear-innovation-responding-to-climate-change-and-strengthening-global-security/" \t "https://www.perplexity.ai/search/_blank). These advanced systems offer zero-carbon energy production at scales capable of supporting economic growth while providing reliable baseload generation that complements variable renewable sources.

The Intergovernmental Panel on Climate Change (IPCC) has emphasized the urgency of limiting global temperature increases to 1.5°C above pre-industrial levels to prevent the most severe climate change consequences[8](https://globalnexusinitiative.org/results/reports/advancing-nuclear-innovation-responding-to-climate-change-and-strengthening-global-security/" \t "https://www.perplexity.ai/search/_blank). Achieving this ambitious target requires rapid, far-reaching transitions across energy systems worldwide—a transformation that benefits from inclusion of all available low-carbon technologies. Advanced nuclear systems, with their ability to provide continuous, weather-independent power without direct carbon emissions, represent an increasingly important tool in this transition, particularly for applications requiring high energy density or constant availability that may be difficult to address through intermittent renewable generation alone.

## Complementary Role with Renewable Energy

Advanced nuclear technologies offer unique capabilities that complement renewable energy sources, potentially enabling higher overall penetration of low-carbon generation than either approach could achieve independently. While solar and wind power have experienced dramatic cost reductions and accelerating deployment, their weather-dependent production profiles create integration challenges as their share of total generation increases. Advanced nuclear systems, particularly smaller and more flexible designs, can provide firm capacity that balances these fluctuations while maintaining grid stability and reliability without carbon emissions.

The complementary relationship between nuclear and renewable generation extends beyond simple backup power functions to include potentially innovative hybrid systems. Advanced reactors designed with enhanced load-following capabilities can adjust their output in response to renewable generation patterns, increasing production during periods of low wind or solar availability and reducing output when renewable generation is abundant. Some reactor designs can also produce hydrogen or industrial process heat during periods of excess renewable generation, effectively storing energy in forms that can be used later or in non-electrical applications. These synergistic approaches maximize the utilization of all carbon-free generation assets while maintaining reliable service to consumers.

## Conclusion

The landscape of nuclear energy is undergoing profound transformation through technological innovation across multiple fronts. From compact, factory-built small modular reactors to revolutionary Generation IV designs incorporating molten salt and thorium fuel cycles, these advancements are addressing historical challenges related to cost, safety, and waste management. Simultaneously, digitalization through artificial intelligence and digital twin technologies is creating new possibilities for operational excellence and remote management that were previously unattainable. Together, these innovations position nuclear energy as an increasingly viable component of global decarbonization strategies.

The evolution of nuclear technology demonstrates how engineering creativity and scientific advancement can transform existing energy systems to meet contemporary challenges. Small modular reactors offer practical near-term solutions that reduce financial risk while maintaining reliability, while more advanced concepts like molten salt reactors and fusion systems promise even greater benefits in subsequent development phases[1](https://www.oecd-nea.org/jcms/pl_71126/examining-the-safety-of-small-modular-reactors" \t "https://www.perplexity.ai/search/_blank)[4](https://inl.gov/molten-salt-reactors/how-molten-salt-could-be-the-lifeblood-of-tomorrows-nuclear-energy/" \t "https://www.perplexity.ai/search/_blank)[6](https://www.iea.org/news/iea-committee-on-energy-research-and-technology-focuses-on-state-and-prospects-of-nuclear-fusion-at-thematic-workshop" \t "https://www.perplexity.ai/search/_blank). This technological progression is occurring alongside growing recognition of nuclear energy's potential contribution to climate change mitigation, with organizations like the Global Nexus Initiative highlighting its importance in providing zero-carbon energy while supporting economic development[8](https://globalnexusinitiative.org/results/reports/advancing-nuclear-innovation-responding-to-climate-change-and-strengthening-global-security/" \t "https://www.perplexity.ai/search/_blank).

As these innovations continue to mature and transition from research to commercial implementation, they will require thoughtful policy frameworks and international cooperation to achieve their full potential. The technical complexity and capital intensity of nuclear development necessitates sustained commitment from governments, industry, and research institutions working in concert. By fostering this collaborative ecosystem and maintaining focus on innovation across the nuclear technology spectrum, societies worldwide can unlock a powerful tool for addressing both climate and energy security challenges while creating new opportunities for sustainable growth and development.

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