

The Next Era of Nuclear Engineering: Beyond Fission

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Abstract

Nuclear engineering is undergoing a significant transformation as emerging technologies push the boundaries of traditional fission-based power generation. This article discusses the next generation of nuclear technologies, including advanced reactor designs, small modular reactors (SMRs), and the growing potential of nuclear fusion. It examines how these innovations are intended to improve safety, enhance fuel efficiency, and reduce the generation of long-lived radioactive waste, which have been longstanding challenges in the nuclear industry. The article also explores how digitalization, artificial intelligence, and advanced materials can contribute to improved reactor performance and reliability. The role of nuclear energy as a foundation for a low-carbon future is examined, particularly in the context of global climate goals and increasing energy demands. The study emphasizes the importance of public acceptance, international cooperation, and regulatory frameworks for the successful implementation of advanced nuclear technologies. It also considers economic factors, including lifecycle management and cost-reduction strategies, which are essential for widespread adoption. Furthermore, recent developments in safety systems, passive cooling technologies, and accident-tolerant fuels are discussed to demonstrate progress toward safer and more resilient nuclear operations. By examining current research, technological advancements, and policy challenges, this work provides a comprehensive overview of how nuclear engineering is evolving to meet the energy needs of the 21st century while prioritizing safety and sustainability.

Keywords: Nuclear engineering, reactors, small modular reactors (SMRs), nuclear fusion, radioactive Waste

INTRODUCTION

The early 21st century heralded a pivotal moment in the history of nuclear engineering, marking a shift toward an advanced paradigm. The pursuit of sustainability, a circular economy, and carbon neutrality in response to climate change, together with advances in various energy technologies, is steering nuclear engineering toward new alternatives that extend beyond the traditional fission paradigm. Next-generation opportunities are represented by several engineering concepts, including (1) fusion or fusion-related processes, (2) advanced fission reactor architectures and fuel cycles implemented in either large-scale designs or small modular reactors (SMRs), and (3) hybrid approaches that synergistically integrate fission and fusion concepts.

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Two primary research questions guide efforts to identify and evaluate next-generation nuclear engineering alternatives:

1. How do these emerging opportunities differ from conventional approaches in ways that justify the pursuit of new paradigms?
2. What is the likelihood that these alternatives will become viable, given that many remain in the early stages of development?

Nuclear fission process of splitting heavy atomic nuclei (such as uranium, thorium, or plutonium)

into lighter nuclei while releasing energy—has played a central role in nuclear engineering. Historical research shows that the evolution of nuclear engineering, from its early concepts to modern technological advancements, reflects changes in scientific knowledge, industrial technology, and, more recently, global environmental concerns. Future opportunities are also expected to evolve in terms of technological maturity and availability in response to changing global conditions [1].

THE HISTORICAL ROOTS OF NUCLEAR ENGINEERING

Many people believe that nuclear engineering began when James Chadwick discovered neutrons in 1932. This marked the beginning of fission technology. During World War II, research on fission was crucial for the development of atomic bombs. This led to the use of large-scale reactors for power generation and other purposes. These early studies helped create the field of nuclear engineering. In 1932, James Chadwick observed neutrons for the first time. In 1939, Lise Meitner and Otto Frisch discovered nuclear chain reactions. In 1942, Enrico Fermi and his team realized that uranium could be used to obtain a large amount of energy. Finally, Eugene Wigner and John von Neumann [2] wrote equations to design large systems and guess how well they would work, including the equation of diffusion of neutrons and the theory of criticality.

Engineering is the art of making things and methods while ensuring that people are safe and healthy. Therefore, when it comes to nuclear engineering, it is very important to know the basic rules, especially when using high-density fuels such as uranium, thorium, and plutonium. Initially, people tried to exploit these fuels and nuclear energy release to generate energy by initiating a fission chain reaction. This is because fusion requires very high temperatures. Subsequently, owing to international agreements on arms control, the focus shifted to fusion because it allows access to energy from H_2 without having to separate isotopes on a massive scale. However, some peaceful uses require a certain level of priority; therefore, efforts have shifted to hybrid systems that combine fission and fusion in the search for more energy options.

THE FISSION PARADIGM: WHAT IT HAS DONE AND WHAT IT CANNOT DO

Although fission-induced neutron multiplication offers nearly limitless energy, sustaining a fission chain reaction over time is difficult. Nuclear engineers have developed several methods to maintain fission. These efforts and the search for new ways to use nuclear energy remain the core focus of nuclear research and development. Fusion energy was considered a possible replacement for fission energy.

The search for fusion energy continues. In the field of fusion, the main areas of research include magnetic and inertial confinement, thermonuclear fusion, and catalyzed fusion. In addition to fusion, improved fission cycles, hybrid systems, and various alternative methods have been proposed. Every idea has its own performance profile and unique promise for generating ultra-clean base-load electricity. One category and a few possibilities, especially enhanced fission cycles, stand out as excellent candidates for broad use in a new era of advanced nuclear capabilities.

THE RISE OF FUSION AND OTHER METHODS

Nuclear fusion remains a distant dream. There has been little research on other options. Current advanced fission methods are based on what we already know, what we can use, and what we already know. Most fusion systems, on the other hand, use materials that are not well known and need big advances in chemistry, materials science, engineering, and astrophysics. Therefore, advanced fission ideas are easier to obtain for research that goes beyond fission.

Multiple avenues are being explored in fusion science. In addition to magnetic and inertial confinement, events observed in astrophysical systems may provide valuable insights. Magnetic and inertial confinement are the two basic methods for keeping things together. Tokamak systems are the most advanced magnetic confinement systems. They work under different plasma conditions. Researchers are also investigating other systems that use different plasma conditions and confinement methodologies.

Advanced fission capabilities may also aid fusion. We already know a lot about fissile fuels, such as deuterium and tritium, and the mechanisms that maintain the neutron/energy balance. Although material problems still exist, they are not as severe as those for full-scale demonstration reactors [3].

ADVANCED REACTOR IDEAS AND SMALL MODULAR REACTORS

Although several sophisticated reactors and SMRs are being developed, they cannot be used because of insufficient experience and competition. Next-generation reactors come in a wide range of styles and materials and use different methods to cool and heat. Safety is a key part of next-generation SMRs, which set them apart from fission reactors. Most designs prefer passive safety; however, the present plans for advanced reactors and SMRs still do not have full safety studies.

SMR initiatives often focus on modularity, which facilitates factory construction, accelerates construction, and improves quality control. However, many of the proposed systems do not fit the common concept of modularity in the industry. There is not yet enough evidence to support other stated SMR benefits, such as cheaper capital costs, support for the growth of less well-known supply chains, and the promotion of new energy markets.

The regulations governing advanced reactors and small modular reactors (SMRs) differ from those applicable to conventional fission systems. Stringent international conventions support the concept of safety in reactor design and operation. These requirements are particularly relevant to Generation IV reactor projects, which involve high-temperature operations, deep coolant pools, leak detection systems, and the use of coolants such as sodium and lead. New reactor concepts outside the core project activities continue to be announced. This indicates that many of the advanced reactor designs currently being proposed are still under development and are not yet commercially available.

FUEL CYCLES, WASTE MANAGEMENT, AND ENVIRONMENTAL FACTORS

There are strong connections among many energy technologies, particularly within the nuclear fuel cycle, as well as between energy production, environmental sustainability, and the development of safe energy systems. The pursuit of inherently safe designs has encouraged the development of innovative reactor concepts, including advanced fission and fusion technologies. These new approaches aim to address the limitations of conventional large-scale fission reactors while improving safety, efficiency, and sustainability. As a result, advanced fuel cycles and recycling technologies can reduce waste generation and extend the utilization of nuclear resources beyond the capabilities of traditional reactor systems.

Private companies, government agencies, national research programs, and academic institutions have continued to support fusion research for a variety of reasons. Reports on long-term energy strategies continue to highlight the importance of fusion as a potential future energy source. Ongoing research aims to develop sustainable fuel cycles and energy systems capable of complementing intermittent renewable energy sources. Key areas of investigation include fuel-cycle management, plasma confinement, inertial confinement fusion, and magnetic confinement fusion technologies. Finally, academic research has contributed significantly to the development of theoretical concepts and practical innovations, many of which have influenced both industrial applications and current policy agendas.

Reprocessing and recycling technologies are not fully addressed within conventional fission systems. A comprehensive evaluation of advanced nuclear technologies could significantly improve the efficiency and sustainability of the nuclear fuel cycle. The use of recycled fuel should be limited to approaches that meet established commercial and industrial standards and have been thoroughly tested and analyzed, while appropriate waste-management strategies should continue to be implemented. Looking beyond 2050, policymakers should consider sustainable long-term energy solutions that complement existing energy systems. The transition toward more sustainable energy pathways requires an independent assessment of both nuclear and non-nuclear technologies. Current nuclear energy

options highlight the limitations of fossil fuel-based systems and underscore the need for innovative, low-carbon technologies capable of supporting future global energy demands in a sustainable manner [4].

MODERN NUCLEAR SYSTEMS' SAFETY, RULES, AND RISK ASSESSMENT

Modern nuclear systems face challenges related to safety, regulation, and risk assessment. The principles of defense-in-depth and a strong safety culture remain fundamental, forming the basis of probabilistic risk assessment methods used to ensure safety throughout a system's life cycle. Risk assessment supports regulatory frameworks, licensing processes, and the safe deployment of next-generation nuclear technologies [5]. Advances in reactor design, safety engineering, and computational tools have enabled more comprehensive safety analyses and the development of inherently safe systems. However, regulatory frameworks for advanced nuclear technologies must continue to build on the extensive safety knowledge and operational experience gained from earlier nuclear programs.

The concept of safety culture has become increasingly important worldwide over the last 20 years. It is now considered a key component of an effective safety management and risk oversight system. Open discussions on the formal promotion of a safety culture in nuclear engineering and related facilities are essential. The role of informatics in ensuring the accurate communication of safety culture principles and practices in nuclear engineering continues to receive attention. One effective way to support this objective is to incorporate evidence of safety culture into the modelling and evaluation of nuclear engineering projects.

GLOBAL ENERGY CONTEXT FOR ECONOMICS AND POLICY

Since the 1970s, nuclear projects worldwide have faced significant challenges in achieving profitability due to high construction costs, extended project schedules, technological uncertainties, and unfavorable market conditions. This has contributed to one of the largest declines in nuclear reactor orders in the history of the industry [6]. Project budgets and schedules have frequently exceeded initial estimates. For example, Finland's Olkiluoto project experienced substantial delays and cost overruns after construction began in 2005. Over the past two decades, the outlook for nuclear energy has fluctuated depending on factors such as safety, efficiency, reliability, and other considerations discussed earlier. In contrast, energy demand is expected to increase in countries such as India and the Philippines, while it is projected to decline in Canada and some European countries [7]. In addition, reductions in capital intensity and energy intensity as a proportion of total expenditure may help extend the availability of fossil fuel resources [1]. A historical review of the development of nuclear engineering, together with an examination of alternative concepts and technologies at various stages of maturity, provides the foundation for a more detailed exploration of the next phase of the field.

RESEARCH FRONTIERS: MATERIALS, REACTORS, AND SIMULATIONS

Next-generation nuclear engineering encompasses a wide range of interrelated concepts. Advanced reactors improve the fission cycle by making it more sustainable, safer, and less waste-producing. Fusion technologies, which build on established knowledge of fission and plasma physics, are expected to provide virtually limitless, safe energy. Emerging concepts based on fission–fusion hybrids, deep geothermal energy, and solar energy have also been proposed as alternative approaches to future energy generation.

This study examines the historical evolution and limitations of these paradigms to evaluate emerging options. The fission paradigm was established around 1950. The first reactors were built between 1942 and 1958, and key discoveries helped define the foundations of classical fission technology. Well-established engineering principles continue to influence reactor design and fuel cycles, particularly in the chemical separation of actinides, the final disposal of high-level radioactive waste, and the management of uranium-, thorium-, and other fertile-mineral resources. However, considerable uncertainty remains regarding the comparative advantages, disadvantages, and safety characteristics of different reactor types. These limitations influenced subsequent developments in the nuclear sector as it evolved beyond conventional fission technologies.

Several decades after the emergence of classical fission, researchers began exploring fusion and other advanced energy concepts. Attention focused on inertial and magnetic confinement approaches, which progressed alongside fission research and stimulated significant advances in spectroscopy, plasma physics, materials science, and reactor-related technologies. Despite unmet expectations, technical challenges, and long development timelines (50–100 years, depending on the objectives considered), civil and commercial fusion programs continue to attract substantial interest. The signatories to the Paris Climate Agreement also seek energy systems that minimize CO₂ emissions, enable effective control of heat generation, and incorporate inherently safe designs that are resistant to severe core damage. Fission–fusion hybrids and other category-independent energy systems that combine features of multiple technologies have received considerable attention. These avenues warrant further investigation as a new era of energy development begins [8, 9].

CONSEQUENCES FOR EDUCATION AND THE WORKFORCE IN A NEW NUCLEAR SECTOR

The next generation of nuclear concepts will not consist solely of novel ideas; rather, it will encompass evolutionary developments derived from the achievements of fission technology and adapted to contemporary environmental, economic, and societal constraints. The nuclear industry requires a permanent workforce possessing a diverse range of expertise across multiple disciplines to support research and development, evaluation, design, modelling, operation, standards development, education, management, and other activities associated with these emerging technologies.

In Chapter 5 of his book *On the Physics of Nuclear Nonproliferation*, Charles P. O'Connor of O'Connor and Associates discusses twelve technical disciplines that are essential to fission, fusion, and other advanced energy systems. He also emphasizes the importance of higher-level educational and professional-development opportunities, including postdoctoral programs and advanced collaborative initiatives. In addition to these workforce requirements, educational institutions must adapt their curricula to provide students with greater exposure to these critical topics.

Emerging concepts and technologies in nuclear engineering have the potential to address global energy and environmental challenges in a safe, reliable, and cost-effective manner. To ensure that future generations benefit from safe, secure, and affordable nuclear energy systems, continued advances in science, technology, and engineering are essential. The exploration and development of advanced fission, fusion, and related technologies will require a highly skilled and well-supported nuclear workforce capable of addressing both current and future challenges.

ETHICAL AND SOCIAL ASPECTS

The acceptance of nuclear engineering and technology by society is a major consideration in the design and development of future energy projects. Technologies that aim to meet growing energy demands while mitigating the impacts of climate change are unlikely to achieve widespread adoption unless ethical concerns and socially significant issues are addressed directly. A review of public perceptions of nuclear energy reveals that, despite significant technological advances, nuclear technologies have not consistently received broad societal support. Although considerable effort has been devoted to improving public understanding of nuclear science and engineering, awareness of the associated technologies and their implications remains limited. Furthermore, many relevant issues extend beyond traditional engineering boundaries and require interdisciplinary approaches involving collaboration among engineers, social scientists, policymakers, and other stakeholders.

The relationship between nuclear technology and environmental justice raises important ethical questions regarding equitable access to energy technologies. Communities lacking access to modern energy systems often remain dependent on combustion-based energy sources and other processes that contribute to air pollution. Historical, economic, and social conditions can restrict access to preferred energy technologies, creating barriers to the adoption of cleaner alternatives. In this context, decisions

regarding the deployment of nuclear energy may be viewed differently by various groups, depending on their access to resources, infrastructure, and technological opportunities.

Intergenerational responsibility, a widely recognized ethical principle in engineering, represents another important consideration. The materials, facilities, and waste management requirements associated with nuclear fission may remain relevant for periods extending far beyond the operational lifetimes of individual reactors. Although advances in waste treatment and transmutation technologies may reduce some long-term challenges, they do not eliminate the responsibility to manage nuclear materials safely over extended timescales. Consequently, societies must consider their obligations to future generations when developing and deploying nuclear technologies.

Next-generation nuclear energy concepts continue to offer the potential for low-carbon energy production while incorporating significant improvements in safety, security, and environmental performance. Advanced reactor designs are generally expected to have shorter operational lifetimes and more manageable waste streams than many earlier systems. Enhanced safety features, passive protection mechanisms, and improved risk-management strategies are intended to reduce the likelihood and consequences of severe accidents. These developments support the broader objective of creating sustainable and publicly acceptable energy systems.

At the same time, continued improvements in nuclear safety, security, and public communication remain essential. Public confidence depends not only on technological performance but also on transparency, effective regulation, environmental stewardship, and meaningful stakeholder engagement. Addressing these factors can help improve public understanding of nuclear technologies and facilitate informed discussions regarding their role in future energy systems.

The significance of ethical and social considerations beyond the traditional fission paradigm demonstrates the need for greater public engagement and education. Failure to address these issues may increase the risk of public misunderstanding and opposition, particularly when the deployment of future nuclear technologies is under consideration [10].

CONCLUSION

Nuclear fission energy remains an essential option for the development of sustainable energy systems and continues to play a central role in nuclear engineering. The fission-engineering paradigm has achieved significant milestones, including the generation of energy equivalent to billions of tonnes of fossil fuel from relatively small quantities of nuclear fuel, the provision of electricity for thousands of household-years from a single kilogram of fresh fuel, and the operation of nuclear power plants at capacity factors approaching 90% over extended operating cycles, resulting in billions of cumulative operating hours worldwide. However, these achievements have not fully resolved societal concerns regarding the long-term management of nuclear waste or the proliferation risks associated with fissile materials such as uranium-235, uranium-233, and plutonium-239. These issues continue to represent important environmental, security, and policy challenges.

Illustrative analyses demonstrate the substantial societal and environmental benefits that could result from replacing even a small fraction of fossil-fuel-based energy generation with advanced nuclear technologies, including very high-temperature reactors (VHTRs), liquid-salt-cooled reactors, thorium fuel cycle systems, and other innovative reactor concepts. Such technologies have the potential to significantly reduce greenhouse gas emissions while supporting reliable energy production. Nevertheless, their large-scale deployment has often faced political, economic, and regulatory barriers, particularly as policymakers simultaneously pursue cost-effective pathways toward carbon neutrality through a variety of energy-transition strategies.

This study examines nuclear fission, nuclear fusion, and other advanced energy pathways, including both nuclear and non-nuclear low-carbon technologies. Among these options, advanced fission systems

have been investigated in the greatest detail and currently represent the most technologically mature pathway for large-scale deployment. The objective of this discussion is to evaluate the engineering approaches, enabling technologies, and experimental tools that may facilitate the realization of the full potential of advanced nuclear energy systems.

Among the advanced fission options under consideration, the VHTR coupled with the thorium fuel cycle remains one of the most extensively studied concepts. This approach offers the potential to support regions that continue to rely heavily on fossil fuels while providing a practical transition pathway toward more sustainable and low-carbon energy systems.

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