Advances in Energy Science and Technology
Vol. 1, No. 3|1 December 2025
AEST

Small modular reactors; A comprehensive review of applications, economic viability, and technology

Saeed Zare Ganjaroodi [a], **Maryam Fani** [a,*]

[a]*Energy and Physics Department, Amirkabir University of Technology, 424 Hafez Ave., Tehran, Iran*

Keywords

Small Modular Reactors (SMRs)
Cost
Safety
NuScale
Sustainable energy

Article Info

DOI: 10.22060/aest.2025.5850

Received date 24 October 2025

Accepted date 12 November 025

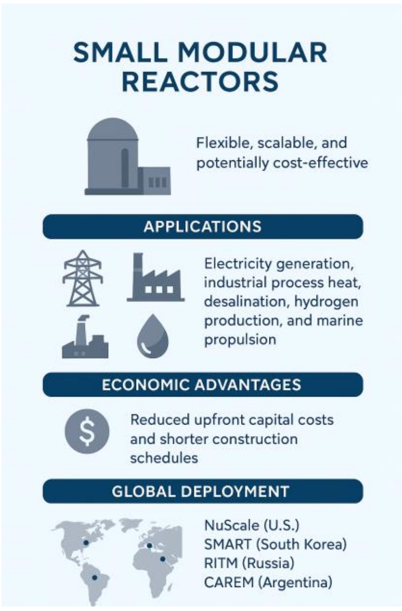
Published date 1 December 2025

* **Corresponding author:**
Mfani@aut.ac.ir

Abstract

Small Modular Reactors (SMRs) are emerging as a flexible, scalable, and potentially cost-effective alternative to conventional large nuclear plants. Characterized by modular construction, compact size, and advanced passive safety systems, SMRs are suitable for regions with limited grid capacity or decentralized energy needs. Their applications extend beyond electricity generation to industrial process heat, desalination, hydrogen production, and marine propulsion, highlighting their potential contribution to global decarbonization and energy transition goals. Economically, SMRs offer reduced upfront capital costs and shorter construction schedules due to modular fabrication, though uncertainties remain regarding long-term competitiveness with large reactors and renewable energy systems. Successful deployment will depend on regulatory frameworks, supply chain readiness, and public acceptance. Global development initiatives such as NuScale (U.S.), SMART (South Korea), RITM (Russia), and CAREM (Argentina) demonstrate technological progress and diverse regional strategies. Overall, SMRs present a promising pathway toward safe, reliable, and low-carbon energy systems, capable of supporting sustainable and resilient energy infrastructures worldwide.

Graphical Abstract



1. Introduction

There has been growing global interest in Small Modular Reactors (SMRs) due to their potential to address some of the key limitations associated with conventional large-scale nuclear power plants. SMRs are being promoted as next-generation nuclear systems that offer improved efficiency, enhanced plant economics, and inherent safety features that make them suitable for a wide range of energy applications. Unlike traditional nuclear reactors, SMRs are designed with a modular approach in which major components can be fabricated in remote factories under standardized conditions and then transported as pre-assembled units to the end-user site. This manufacturing strategy not only reduces on-site construction times and capital investment risks but also increases quality assurance, scalability, and adaptability to diverse energy markets. According to the International Atomic Energy Agency (IAEA), modular reactors are generally classified based on their electrical output capacity. Medium-sized SMRs are capable of producing less than 700 MWe, while small-sized SMRs typically generate less than 300 MWe. This categorization reflects their suitability for deployment in both grid-connected and off-grid applications, particularly in regions with limited infrastructure, isolated communities, or energy systems requiring flexible and incremental capacity additions. In addition to electricity generation, SMRs can be utilized for a variety of non-electric applications such as district heating, industrial process heat, seawater desalination, and hydrogen production, thereby contributing to broader energy diversification and decarbonization strategies [1-5].

Technological innovation in the SMR domain encompasses a diverse range of reactor concepts currently under development across the globe, each with unique design philosophies, performance characteristics, and target applications. Among these, advanced water-cooled reactors represent the most mature and widely pursued category, as they build upon the established safety and operational experience of traditional light-water reactor designs. These include pressurized water reactors (PWRs), boiling water reactors (BWRs), and integral pressurized water reactors (iPWRs), the latter of which integrate the steam generators, pressurizer, and reactor core into a single pressure vessel. Such designs simplify system layouts, reduce the number of large components, and enhance safety by limiting the potential for large-break loss-of-coolant accidents. Another promising category is the high-temperature gas-cooled reactors (HTGRs), which employ helium as a coolant and graphite as both a moderator and structural material. Operating at temperatures that can exceed 750°C, HTGRs are capable of delivering not only high-efficiency electricity but also high-quality process heat for industrial applications, such as hydrogen production through thermochemical cycles or advanced manufacturing processes. Their fuel typically consists of TRISO-coated particles, which offer excellent containment of fission products and resilience under extreme conditions, thus reinforcing the safety case of these reactors. Liquid-metal-cooled fast reactors are also under significant investigation. These include sodium-cooled fast reactors (SFRs) and lead- or lead-bismuth-cooled fast reactors (LFRs). Such systems operate with fast neutron spectra, which enable more efficient utilization of fissile material and the possibility of breeding new fuel from fertile isotopes such as uranium-238. Moreover, they can significantly reduce long-lived radioactive waste by transmuting actinides into shorter-lived isotopes. While sodium cooling offers excellent heat transfer properties, it introduces chemical reactivity challenges, whereas lead-based coolants provide inherent safety advantages such as high boiling points and chemical stability, though they raise issues related to material corrosion. In addition, gas-cooled fast reactors (GFRs) are being studied as part of Generation IV reactor concepts. They employ helium as the coolant and operate at high temperatures while maintaining a fast neutron spectrum. GFRs combine the advantages of high thermal efficiency with the fuel cycle benefits of fast reactors, although challenges remain in fuel development and core materials. Finally, molten salt reactors (MSRs) represent one of the most innovative SMR concepts. MSRs can operate with liquid fuel dissolved in a molten salt mixture or use solid fuel with molten salt as a coolant. Their low operating pressure, strong negative temperature coefficients, and ability to incorporate online refueling and reprocessing make them inherently safe and highly flexible. Moreover, MSRs offer compatibility with thorium-based fuel cycles, opening pathways to more abundant and potentially sustainable nuclear fuel resources. Their capability to deliver high outlet temperatures also makes them suitable for advanced cogeneration applications, including hydrogen and synthetic fuel production [6-10].

The economic dimension of SMRs is one of the most critical factors influencing their feasibility and global adoption. Unlike large conventional reactors, which require significant upfront investment and long construction periods, SMRs are designed for modular fabrication in factory settings, allowing for economies of series production and reduced on-site labor costs. This approach lowers the initial capital expenditure and mitigates the financial risks typically associated with nuclear megaprojects. Furthermore, their smaller unit size enables incremental capacity additions, making them attractive to countries or utilities with constrained financial resources or smaller grid systems. However, economic viability remains contingent upon achieving sufficient market demand to justify large-scale manufacturing, as well as streamlining regulatory and licensing processes to avoid cost overruns. While the levelized cost of electricity (LCOE) from SMRs is projected to be competitive with fossil fuels and, in some cases, renewables, uncertainties around supply chain maturity, waste management, and financing models continue to pose challenges. Overall, the long-term success of SMRs in energy markets will depend on their ability to balance affordability, reliability, and scalability while contributing to global decarbonization objectives [11-13].

Although a substantial body of papers and numerous technical reports have been published globally on SMRs, different aspects from design to deployment, many critical areas remain underexplored due to the emerging nature of the technology and its strategic importance [14-20]. The novelty of SMRs, coupled with their potential to revolutionize nuclear energy systems, has created gaps in research, particularly in areas such as long-term operational performance, regulatory frameworks, integration into existing energy infrastructures, and socio-economic impacts. This underscores the need for continued and comprehensive investigation to fully understand and harness the capabilities of SMRs. *Anthony Asuega et al.* have investigated the cost competitiveness of SMRs compared to both conventional nuclear power and fossil fuel-based systems in 2023. Early assessments suggested that the modularization of reactor components could reduce construction time and financial risk, although economies of scale remain a challenge. Recent research has further explored the levelized cost of electricity (LCOE) of SMRs in comparison with natural gas and coal-fired power plants, both with and without carbon capture and storage (CCS) [21]. In 2025, *Gustavo Alonso* analyzes several economic factors under different electricity-selling prices to determine the possible role of SMRs as a complement or competitor to large reactors. Results show that for low electricity-selling prices, an SMR is a complementary infrastructure but can be a market competitor for higher prices. The study also provides information about the required economic scenario where nuclear reactors, small and large, could be part of the net-zero policy from a financial point of view [22]. *Nick Van Hee et al.* found an average capital cost of €7.031/kW and an average levelized cost of electricity of 85€/MWh for small modular reactors, while capital costs were found to be on average 41% higher than for the large reactors. Carbon and gas prices are not included in this cost estimate, yet these volatile prices also affect small modular reactor costs [23].

The significance of conducting thorough research on SMRs lies in their transformative potential to redefine the future landscape of nuclear energy by overcoming longstanding technological, economic, and environmental barriers that have limited the expansion of large-scale nuclear projects. A comprehensive examination of their applications, economic feasibility, and diverse designs offers an integrated perspective on how SMRs can be effectively incorporated into contemporary energy systems. This study explores various reactor technologies and emphasizes the distinct benefits and compromises associated with each in terms of safety, efficiency, scalability, and sustainability. Moreover, investigating SMRs' potential roles in electricity generation, industrial heat supply, hydrogen production, and desalination highlights their versatile contribution toward achieving global energy demands and decarbonization targets. Economic analysis further reveals how modular construction techniques, lower upfront costs, and adaptable deployment strategies may improve access for nations with constrained infrastructure and financial capacity. Ultimately, this research not only advances the scientific and technical understanding of SMR technologies but also equips policymakers, investors, and energy strategists with critical insights to make informed decisions that support secure, reliable, and low-carbon energy futures.

2. Review Strategy

This study adopts a structured review strategy to deliver a comprehensive evaluation of SMR technologies, systematically addressing three interrelated dimensions: technological innovation, sectoral applications, and economic viability. From a technological standpoint, the review emphasizes advancements in reactor design that differentiate SMRs from conventional large-scale nuclear reactors. Key areas of focus include modular construction techniques, passive and inherent safety mechanisms, and the integration of advanced fuel cycles. Particular attention is given to both light-water and non-light-water SMR configurations, with comparative analysis of cooling methodologies, neutron spectra, and scalability prospects. To capture the current landscape of SMR development, the study synthesizes insights from peer-reviewed literature, technical documentation, and case studies drawn from international SMR initiatives. This includes an examination of ongoing pilot projects and emerging trends that signal future directions in reactor deployment and innovation.

Beyond technological considerations, the review explores the diverse applications of SMRs across multiple sectors. These include electricity generation, industrial process heat, desalination, hydrogen production, and marine propulsion. By assessing these use cases, the study highlights the potential of SMRs to enhance energy access in remote or infrastructure-limited regions and to support decentralized energy systems.

Economic analysis is conducted in parallel, focusing on the financial and logistical advantages of modular construction, such as reduced upfront capital requirements, accelerated build timelines, and improved cost competitiveness over the plant lifecycle. The review also considers how SMRs compare economically with traditional nuclear facilities and renewable energy alternatives. By integrating these three dimensions, technological, functional, and economical, the study offers a holistic framework for understanding SMR deployment potential. This approach not only informs future research trajectories but also provides actionable insights for policymakers, industry stakeholders, and energy planners seeking to navigate the evolving nuclear energy landscape.

2.1. SMR Technology

SMRs represent a new generation of nuclear technology distinguished from traditional large-scale reactors by their compact size, modular construction, and advanced safety features. Unlike conventional reactors, which require complex on-site construction and high capital investment, SMRs are factory-fabricated and transported to deployment sites, significantly reducing costs and construction times (**Fig.1**). Their modularity allows for incremental capacity expansion according to demand, while advanced passive safety systems minimize reliance on operator intervention in emergencies, thereby addressing long-standing public concerns about nuclear safety. Moreover, SMRs can integrate multipurpose applications such as district heating, desalination, and isotope production, functions rarely considered in older reactor designs. This combination of scalability, versatility, and enhanced safety positions SMRs as a transformative alternative to traditional

Vol. 1, No. 3|1 December 2025
Advances in Energy Science and Technology
AEST

nuclear power plants in both established and emerging energy markets [24]. Different types of SMR designs based on power range are shown in **Fig.2**.

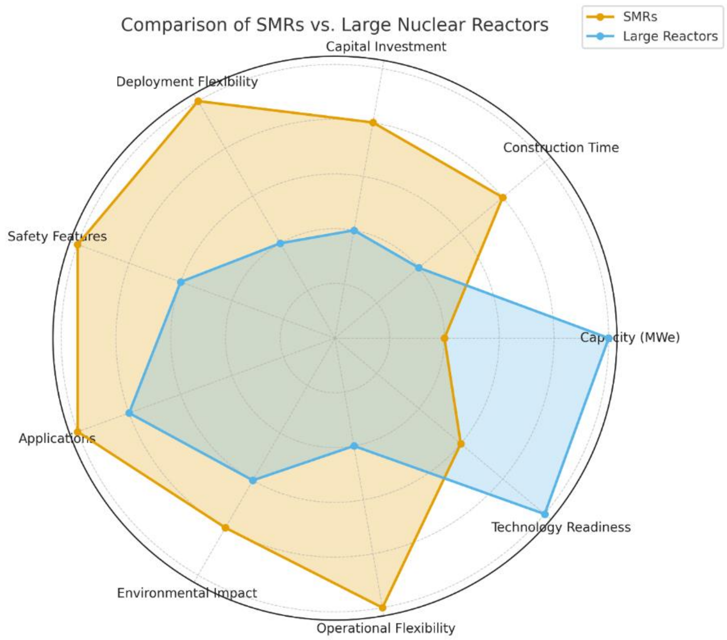


Fig.1. Comparison of large nuclear reactors and SMRs across system design, technology, safety, and operational features.

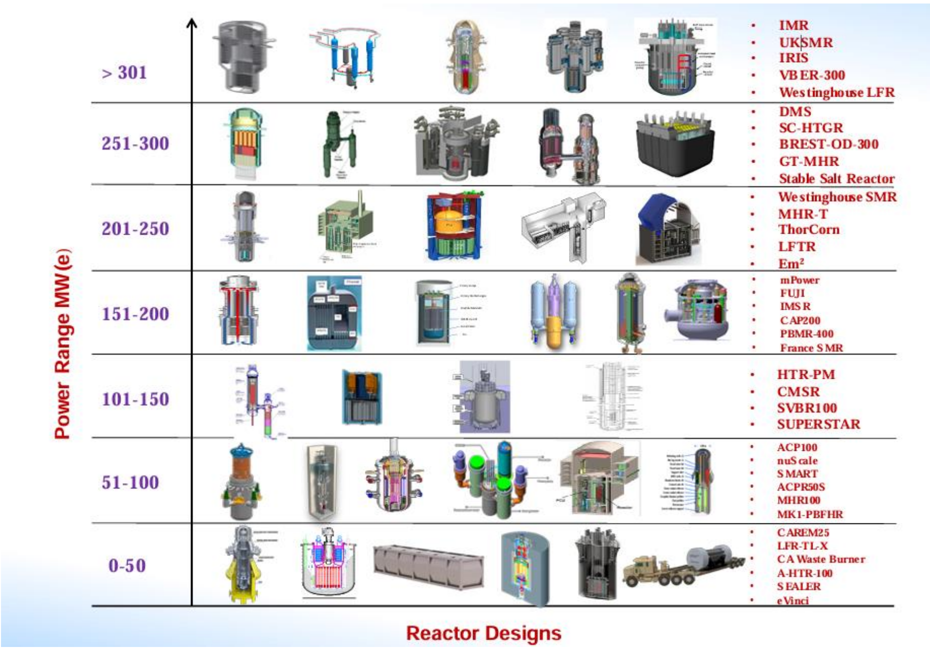


Fig.2. Classification of SMR designs according to their power output range [25].

Recent international reports indicate that the number of SMR designs is expanding rapidly. Estimates vary, ranging from more than 80 to over 120 conceptual and developmental designs worldwide, reflecting the diversity of technological approaches and growing investment interest. A significant share of these designs has attracted funding or governmental support, with pilot projects, demonstration units, and early-stage construction concentrated in North America, Europe, Russia, and China (**Fig.3**). The United States currently leads in the number of design organizations, while several European countries have initiated national programs or industrial partnerships for future SMR deployment. At the national level, the United States, Russia, and China are considered global frontrunners, with the latter two having already launched operational floating or grid-connected SMR units such as the KLT-40S and RITM series. Other active players include the United Kingdom, Canada, South Korea, and emerging European markets such as Poland and the Czech Republic, which are pursuing SMR projects through bilateral agreements and industrial collaborations. Despite this momentum, only a limited number of SMRs have reached full commercial operation, while the majority remain in design, licensing, or construction phases. Nonetheless, the geographical spread of ongoing initiatives highlights the strategic importance of SMRs in diversifying clean energy portfolios and advancing nuclear innovation worldwide [24-25].

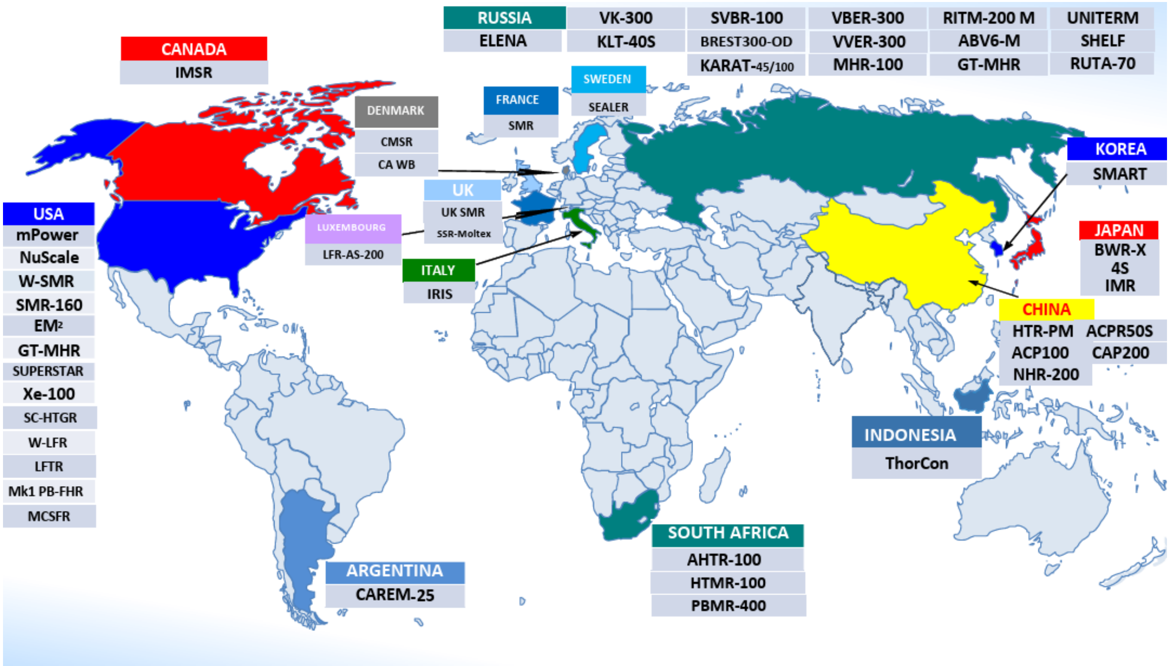


Fig.3. SMR technology development worldwide [25].

Land-based SMRs are typically water-cooled systems that rely on established light-water reactor (LWR) fuel technologies, with U-235 enrichment levels below 5%. Their refueling cycles generally range between 18 and 24 months, achieving high burnup values above 45 GWd/tHM while maintaining capacity factors over 90%. By closely resembling existing large-scale water-cooled designs, these SMRs can leverage mature regulatory frameworks and existing supply chains, thereby reducing both operational costs and technological uncertainties. Their design priority is to combine proven reactor safety features with economic efficiency, making them suitable for deployment in regions with established nuclear infrastructure. Marine-based SMRs, by contrast, adopt higher fuel enrichment levels up to about 20% to support extended refueling cycles as long as 10 years, ensuring autonomous operation in remote or offshore locations. Examples include the Russian KLT-40S, used in the floating nuclear plant Akademik Lomonosov, and the more advanced RITM-200M, which is optimized for long service intervals and secure return of spent fuel to the country of origin for reprocessing. In addition, high-temperature gas-cooled SMRs (HTGRs), such as China's HTR-PM and General Atomics' EM2 design, highlight a parallel trajectory in reactor innovation. Using TRISO-coated particle fuel and prismatic or pebble-bed configurations, these reactors offer enhanced safety, very high thermal efficiency, and potential lifetimes extending beyond three decades without refueling.

Together, these land-based, marine-based, and gas-cooled SMR designs illustrate the technological diversity of the field, addressing different operational environments and energy demands [25].

SMRs integrate a range of advanced technologies that distinguish them from conventional nuclear reactors. Among the most important are passive safety systems, which rely on natural circulation, gravity, and convection rather than active mechanical components, ensuring automatic shutdown and cooling in emergency scenarios without operator intervention. In addition, many SMR designs employ integral reactor configurations, where the reactor core, steam generators, and pressurizers are housed within a single pressure vessel. This compact arrangement reduces the risk of large-scale coolant loss and simplifies the overall reactor system. Furthermore, modular construction methods allow SMRs to be factory-fabricated and transported to deployment sites, reducing construction time, standardizing quality, and lowering capital costs compared to large-scale plants. Another critical area of innovation is fuel and core technology. Advanced fuel forms such as TRISO-coated particle fuel used in HTGRs provide enhanced fission product retention and accident tolerance, while innovative cladding materials improve resistance to corrosion and radiation damage. Certain SMR designs also incorporate long refueling cycles ranging from several years to multiple decades through higher fuel enrichment levels or online refueling capabilities, making them suitable for remote locations and continuous operation. Additionally, some advanced SMRs, including molten salt reactors (MSRs) and sodium-cooled fast reactors (SFRs), utilize alternative coolants and fuel cycles to achieve higher thermal efficiencies, flexibility in fuel utilization, and waste minimization. Collectively, these technological advances position SMRs as not only smaller-scale reactors but as platforms for next-generation nuclear innovation, balancing safety, efficiency, and sustainability [26-27]. The overview of SMRs and their key features is listed in **Table 1**.

Table 1. Overview of SMRs and their key features: Compact, flexible, and safer nuclear technology for modern energy needs.

Feature	Description
Reactor Type	Small, modular reactors designed to generate less energy than traditional large reactors
Thermal / Electric Power	Typically between 10 and 300 MWe (megawatts electric)
Size & Modularity	Small units, modular design, allows gradual capacity expansion
Fuel type	Usually low- to medium-enriched uranium; some designs use thorium
Design life	40 to 60 years
Cooling System	Light water, heavy water, gas, molten salt, or liquid metal depending on design
Safety and security	Passive safety features, reduced need for human intervention in emergencies
Deployment Flexibility	Can be installed in remote areas, small grids, or industrial sites
Capital cost	Lower than large reactors, factory-built and assembled on-site
Greenhouse Gas Emissions	Near zero during electricity production
Applications	Electricity generation, industrial heat, hydrogen production, remote energy supply, grid stabilization

2.2. Applications

SMRs are an emerging nuclear technology designed to provide flexible, safe, and reliable sources of energy. Unlike traditional large-scale nuclear power plants, SMRs are smaller in size and modular in design, allowing them to be manufactured in factories and deployed on-site with reduced construction time and cost. Nuclear power projects are often associated with high capital costs, particularly when compared to renewable energy technologies. To improve the return on investment (ROI), it is essential to integrate multiple applications in a coordinated manner. In this context, two major categories of utilization can be identified as multipurpose irradiation applications, which are mainly employed in research reactors and in some SMR designs, and cogeneration or secondary thermal applications, where nuclear power plants are used for non-electrical purposes such as district heating, desalination, or industrial heat supply.

One of the most important applications of SMRs is electricity generation, particularly in remote areas or regions with limited access to large power grids. Their scalability makes them suitable for countries that do not require or cannot afford large nuclear facilities. By deploying multiple SMR units, power generation can be expanded step by step according to demand. Beyond electricity, SMRs have valuable non-electric applications. These include providing process heat for industrial operations, district heating for cities, and desalination of seawater to address water scarcity. Additionally, SMRs are being considered for powering military bases, isolated communities, and data centers, where a secure and uninterrupted energy supply is critical. Another significant advantage of SMRs lies in their enhanced safety features. Many designs incorporate passive safety systems that allow the reactors to shut down automatically in case of an emergency without human intervention. This makes them an attractive option for countries aiming to expand nuclear energy while minimizing safety concerns [28-29].

Nuclear research reactors have a wide range of neutron irradiation applications, including radioisotope production, Neutron Activation Analysis (NAA), Neutron Transmutation Doping (NTD), neutron radiography, medical therapies such as Boron Neutron Capture Therapy (BNCT), geochronology, gemstone coloring, radiation damage studies on structural materials and ICs, material structure analysis, destructive and non-destructive fuel testing, radioactive nuclear safety tests, and prototype testing of new reactor designs. Research reactors (RRs) can be classified as neutron sources, subcritical assemblies, zero-power reactors, low-power reactors such as Miniature Neutron Source Reactors (MNSRs), conventional pool-type Material Testing Reactors (MTRs), advanced Multi-Purpose Research Reactors (MPRRs), and high-flux reactors for advanced material and fuel testing. Designing multi-purpose reactors that can efficiently address multiple irradiation applications simultaneously is considered the most economically and technically effective approach. Typically, these reactors are open pool-type designs with plate-type fuel assemblies and, in modern versions, incorporate reflector tanks (e.g., using D_2O) and passive emergency shutdown systems [30-31].

Among Small Modular Reactors (SMRs), the RUTA-70 is currently the only multi-purpose design explicitly intended for irradiation applications. It is a water-cooled, water-moderated integral pool-type reactor with 70 MW thermal capacity, providing nuclear district heating, desalination, and radioisotope production for medical and industrial use. Other SMR designs, such as the DHR-400, primarily focus on district heating but may have the potential for multi-purpose irradiation applications after modifications. However, these SMRs remain conceptual designs, in contrast to the many operational MTRs and multi-purpose research reactors worldwide. For SMRs, the most feasible irradiation application at present is radioisotope production. Many industrial and medical radioisotopes require specific operating conditions and long irradiation times, which can be met by certain SMR designs, including thermal spectrum SMRs (iPWRs, BWRs, PHWRs) and online refueling reactors (especially PHWRs) or online processing reactors (such as MSRs). For instance, conventional PHWRs (e.g., PHWR-220) produce essential industrial isotopes like Co-60, while newer SMR designs, including AHWRs and MSRs, show potential for enhanced isotope production through online fuel processing [32-34].

SMRs have significant potential for non-electrical industrial applications, often referred to as thermal applications. These include seawater desalination, district or regional heating, ethanol concentration, petroleum refining, biomass gasification, coal gasification, liquid hydrogen production, and steel manufacturing. The suitability of an SMR for a given application strongly depends on its operating temperature, with higher temperatures enabling more efficient thermochemical processes. Water-cooled SMRs (such as PWRs, iPWRs, BWRs, PHWRs, AHWRs) are ideal for low-temperature applications such as desalination and district heating, while high-temperature SMRs (such as LMFBRs, MSRs, GCRs, VHTGRs) support processes like hydrogen production or high-temperature chemical conversions. Cogeneration, combining electricity production with thermal industrial use, is a key concept for many SMRs, exemplified by designs such as DHR-400 and KLT-40S, which integrate safe, carbon-free electrical and thermal outputs. These applications emphasize the role of SMRs in supporting industrial processes while contributing to carbon neutrality goals, though rigorous safety standards and operational codes remain essential for hybrid nuclear-industrial plants [35].

Deep space missions, particularly those targeting Mars, face significant energy challenges that limit the long-term reliability of solar panels. Factors such as dust accumulation, seasonal variations, long distances from the Sun, and unforeseen mission demands can severely reduce energy efficiency and threaten operational success. To overcome these limitations, alternatives such as nuclear batteries have been employed. For example, NASA's Curiosity and Perseverance rovers utilize Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs), which convert the decay heat of Pu-238 into electricity and thermal energy, ensuring a continuous power supply and protection against freezing conditions on Mars [36-37].

However, the growing complexity and extended duration of future space missions are expected to require more robust power systems exceeding the capabilities of solar panels and MMRTGs. In response, NASA has developed and tested the Kilopower reactor, a compact nuclear fission system utilizing heat pipe technology, passive safety mechanisms, and Stirling engines to deliver 1–10 kW of electricity. Such micro reactors offer greater sustainability, resilience, and efficiency, enabling faster interplanetary travel, long-term exploration, and reliable operation in extreme environments. Historically, both the U.S. and Soviet Union have launched space nuclear power systems, and recent innovations in heat-pipe-based micro reactors (MMRs) build on these foundations to provide ultra-safe, autonomous, and long-lived power supplies. Beyond space applications, MMR technology shows promise for terrestrial use in remote or energy-constrained environments such as Arctic regions, isolated islands, or large facilities like hospitals. Companies such as Westinghouse are developing designs like eVinci, inspired by space-class nuclear reactors, to provide resilient, transportable, and sustainable power solutions. As both space agencies and industry leaders advance these technologies, frameworks such as NASA's Technology Readiness Level (TRL) and Westinghouse's Manufacturing Readiness Level (MRL) help assess maturity and commercialization pathways. Ultimately, small modular nuclear reactors are expected to play a central role in the future of deep space exploration and remote terrestrial energy supply [36-38].

2.3 Economic Analysis

The cost of nuclear-generated electricity remains relatively high compared to many conventional and renewable energy sources, primarily due to the substantial upfront capital investment required for plant construction, long licensing procedures, and complex regulatory compliance. Large-scale nuclear reactors demand extensive on-site construction, advanced safety systems, and specialized materials, all of which contribute to elevated levelized costs of electricity (LCOE). While operational and fuel costs are comparatively low and stable, the significant initial expenditure often makes nuclear power more expensive per kilowatt-hour than natural gas, coal, or wind and solar in regions with low construction costs. SMRs aim to address some of these economic challenges by reducing construction times, standardizing components, and enabling incremental capacity expansion, potentially lowering the financial barriers to entry and improving economic feasibility for new nuclear projects [39-40].

High capacity factors significantly enhance the economic performance of nuclear facilities, and this parameter is critical for both large reactors and SMRs. Achieving high capacity requires efficient refueling strategies, minimizing unplanned shutdowns, and implementing scheduled maintenance. For SMRs, attaining a capacity factor comparable to or exceeding that of current light-water reactors is essential to maintain competitiveness in design, construction, and deployment. Vendors of SMRs commonly claim capacity factors of 95% or higher, demonstrating the potential for high operational efficiency despite smaller unit sizes. This factor, combined with modularity and factory fabrication, allows SMRs to achieve consistent output while managing capital and operational risks effectively [41].

The economic advantage of SMRs extends beyond operational efficiency. Shorter construction schedules, typically 4–5 years for early and subsequent units, reduce the financial burden and accelerate electricity generation compared to large reactors, which may require 5–6 times longer to reach completion. Modular design, standardized components, and factory-based production contribute to reduced construction times, lower error rates, and enhanced quality control. By repeating the fabrication of standardized modules, SMRs benefit from learning effects, progressively reducing costs with each successive unit. Historical evidence from shipbuilding indicates that controlled factory conditions and serial production can significantly improve efficiency and reduce labor hours, a principle directly applicable to SMR construction [42] (**Fig.4**).

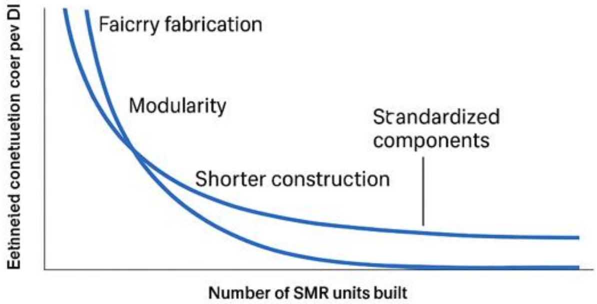


Fig.4. SMR economic analysis view.

Financial flexibility is another key factor driving the attractiveness of SMRs. Large-scale reactors often impose substantial upfront capital requirements, potentially creating significant strain on a company's balance sheet. In contrast, SMRs allow incremental investment, spreading financial risk over multiple units and enabling smaller companies to participate in nuclear projects without committing billions of dollars to a single plant. Economies of series production, along with shorter construction timelines, contribute to faster returns on investment and LCOE. Cost modeling indicates that design simplification can reduce capital expenses by up to 15%, shorter construction periods by up to 20%, and multi-unit deployment can yield additional reductions of 10–25%, cumulatively lowering the cost per kilowatt for SMR-generated electricity [43-44].

Table 2. Key economic parameters of SMRs vs large reactors.

Parameter	Large nuclear reactor	SMR
Capacity factor (%)	90	95% or higher
Construction time (Year)	5-10	4-5
Capital Investment per Unit	Very high ($billions)	Lower per module
Learning Effect / Cost Reduction	Limited	Significant
Design complexity	High	Simplified, modular
LCOE	Moderate to high	Competitive with large reactors

Operational and maintenance costs for SMRs are expected to be lower than those of large reactors, owing to simplified systems, fewer components, and passive safety mechanisms. While fuel costs per unit may be slightly higher due to lower core volumes, savings in management, operations, and maintenance compensate for these differences. Moreover, modular design facilitates parallel construction and onsite assembly, reducing installation complexity and improving reliability. These factors collectively position SMRs as economically viable alternatives to conventional large reactors, particularly in markets where financial flexibility, rapid deployment, and scalability are crucial [43-44]. Key economic parameters of SMRs compared with large reactors are presented in **Table 2**.

3. Discussion

SMRs represent a significant evolution in nuclear technology, primarily characterized by their compact scale, modular construction, and integration of advanced safety mechanisms. By shifting fabrication from conventional on-site construction to controlled factory environments, SMRs substantially reduce both capital expenditures and project timelines, while enabling standardized quality control across multiple units. Their modularity provides flexible capacity deployment, allowing incremental scaling that aligns with demand fluctuations. A defining feature of SMRs lies in their passive safety systems, which minimize dependence on active mechanical components or operator intervention. Leveraging natural circulation, gravity-driven cooling, and integral reactor designs, these systems inherently enhance operational safety by mitigating risks associated with coolant loss or emergency shutdown scenarios. Integral configurations, where the reactor core, steam generators, and pressurizers coexist within a single vessel, further simplify reactor architecture and reduce vulnerability to system failures.

SMRs also demonstrate substantial technological diversity. Land-based water-cooled variants typically adopt proven light-water reactor fuels with standard enrichment levels, enabling compatibility with existing regulatory frameworks and supply chains. Marine-based units operate with higher enrichment to support extended refueling intervals, addressing the logistical constraints of remote or offshore deployment. Meanwhile, high-temperature gas-cooled designs employ TRISO-coated fuel particles and innovative core geometries, achieving enhanced thermal efficiency, prolonged operational lifetimes, and elevated safety margins. Other advanced configurations, including molten salt and sodium-cooled fast reactors, incorporate alternative coolants and fuel cycles to optimize thermal performance, fuel utilization, and waste management. Across all designs, modular fabrication, advanced fuel technologies, and passive safety integration collectively define SMRs as a platform for next-generation nuclear innovation. These features allow for streamlined deployment, improved operational reliability, and scalability while maintaining high safety and efficiency standards. The diversity of SMR technologies, encompassing land-based, marine-based, and gas-cooled systems, underscores their adaptability to different operational environments and highlights their potential to reshape nuclear engineering paradigms.

While SMRs offer strong potential as flexible and scalable sources of carbon-free energy, their deployment is not without significant challenges. High capital intensity relative to renewables, lengthy licensing processes, and public concerns over nuclear safety can slow down their acceptance. Moreover, questions remain about the economic competitiveness of SMRs in liberalized energy markets, particularly when cheaper alternatives such as solar and wind are rapidly expanding. The success of SMRs, therefore, depends on coordinated policy support, strong regulatory frameworks, and clear pathways for commercialization that address not only technical feasibility but also societal acceptance.

The multifunctional applications of SMRs, ranging from isotope production to district heating and industrial cogeneration, can improve return on investment and justify their deployment. However, integrating irradiation or non-electric applications into reactor design increases complexity, requiring rigorous safety protocols and international harmonization of standards. For instance, coupling nuclear reactors with industrial processes such as desalination or hydrogen production raises questions of operational safety, liability, and emergency response. These challenges highlight that while SMRs may provide an opportunity to redefine nuclear energy as more versatile and decentralized, their hybrid role also magnifies regulatory and technical demands. In parallel, the extension of SMR and micro reactor technologies to space exploration demonstrates both the promise and the difficulty of pushing nuclear systems beyond traditional contexts. Although space applications showcase the resilience of nuclear systems in extreme environments, translating these innovations to Earth requires overcoming distinct socio-political barriers. Public trust, proliferation risks, and waste management remain central obstacles that could undermine otherwise promising advances. Thus, the future of SMRs will not be determined by engineering achievements alone but by how effectively governments, industries, and societies navigate the intersection of technology, safety, and public legitimacy.

The economic performance of nuclear power is heavily influenced by capital intensity, regulatory complexity, and construction duration. Traditional large reactors incur substantial upfront expenditures due to extensive on-site construction, advanced safety systems, and specialized materials, which drive high LCOE despite relatively low operational and fuel costs. SMRs address these challenges through modularization, standardized components, and factory-based fabrication, which shorten construction schedules and reduce labor and error-related costs. By enabling incremental capacity deployment, SMRs also mitigate financial risk, allowing a more gradual allocation of investment and enhancing feasibility for smaller utilities or markets with constrained capital availability. Serial production further introduces learning effects, progressively lowering unit costs and improving economic competitiveness relative to large-scale nuclear installations.

Operational efficiency remains a critical determinant of SMR economics. High capacity factors comparable to those of conventional light-water reactors are essential to optimize returns and stabilize LCOE. SMR designs leverage passive safety features, simplified systems, and streamlined maintenance requirements to maintain consistent output while minimizing downtime. Combined with reduced construction timelines and modular deployment, these characteristics enhance financial flexibility, accelerate revenue generation, and lower per-unit electricity costs. Consequently, SMRs offer a pathway to economically viable nuclear energy, particularly in regions where rapid deployment, scalability, and controlled capital exposure are strategic priorities.

Finally, SMRs present significant technical opportunities by combining modular construction, advanced passive safety systems, and diverse reactor technologies, enabling scalable, flexible, and safer nuclear power deployment. Their compact size allows integration into sites unsuitable for large reactors, while factory fabrication can reduce construction time and improve quality control. However, SMRs also face several challenges, including higher unit costs per megawatt compared to large reactors, limited operational experience, and the need for regulatory frameworks tailored to novel designs. Additionally, supply chain development, licensing complexity, and public perception remain critical hurdles that must be addressed to fully realize the technical and economic potential of SMRs in global energy markets.

4. Conclusion

SMRs represent a significant evolution in nuclear power, offering a unique combination of safety, scalability, and versatility that distinguishes them from conventional large-scale reactors. This review has highlighted the breadth of SMR applications, extending beyond electricity generation to include process heat, desalination, hydrogen production, and marine propulsion, underscoring their potential as a multipurpose energy solution aligned with global decarbonization goals. Economically, SMRs show promise through reduced upfront costs and modular construction techniques, though questions remain regarding long-term competitiveness and integration with existing energy markets. The global development landscape demonstrates both technological diversity and regional adaptation, with initiatives showcasing progress toward commercialization. However, challenges related to regulatory approval, supply chain maturity, and public acceptance must be addressed to enable large-scale deployment. Ultimately, SMRs are not a universal replacement for all energy systems but rather a complementary solution that can bridge gaps in energy access, enhance grid resilience, and accelerate the transition toward sustainable, low-carbon infrastructures. By overcoming economic and policy barriers, SMRs hold the potential to play a pivotal role in shaping the future of nuclear energy and supporting the broader goals of global energy transition. By combining modular fabrication, diverse reactor technologies, and passive safety mechanisms, SMRs offer enhanced deployment flexibility and operational reliability across a range of applications. Their compact scale and factory-based construction support accelerated project timelines and improved quality control, reinforcing economic feasibility. Realizing their full potential will depend on overcoming regulatory, market, and societal challenges while leveraging the inherent adaptability of these advanced nuclear systems.

Ethical Consideration

The authors of the article certify that all ethical principles related to research have been completely met.

Conflicts of Interest

The authors declared that they have no conflicts of interest in this paper. Also, we declare the following financial interests that represent a conflict of interest in connection with the research works submitted.

Data availability

The data that has been used is confidential.

References

[1] C. A. Lloyd, T. Roulstone, R. E. Lyons, Transport, constructability, and economic advantages of SMR modularization. Prog. Nucl. Energy, 134 (2021), 103672.

[2] B. Daigle, S. De Carlo, N. Lotze, U.S. International Trade Commission, Big change goes small: Are small modular reactors (SMRs) the future of nuclear energy? Off. Ind. Compet. Anal. Work. Pap., ICA-105 (2024).

[3] F. Boarin, M.E. Ricotti, An evaluation of SMR economic attractiveness. Sci. Technol. Nucl. Install., 2014 (2014), 803698.

[4] G. Locatelli, C. Bingham, M. Mancini, Small modular reactors: A comprehensive overview of their economics and strategic aspects. Prog. Nucl. Energy, 73 (2014), 75–85.

[5] S. Z. Ganjaroodi, M. Fani, E. Zarifi, S. Bentridi, Thermal-hydraulic modeling of CAREM-25 advanced small modular reactor using the porous media approach and COBRA-EN modified code. Nucl. Eng. Technol., 56 (5) (2024), 1574–1583.

[6] D. Zhang, L. Liu, M. Liu, R. Xu, C. Gong, J. Zhang, C. Wang, S. Qiu, S. Su, Review of conceptual design and fundamental research of molten salt reactors in China. Int. J. Energy Res., 42 (5) (2018), 1834–1848.
Zendy

[7] J. Wu, J. Chen, X. Cai, C. Zou, C. Yu, Y. Cui, A. Zhang, H. Zhao, A review of molten salt reactor multi-physics coupling models and development prospects. Energies, 15 (21) (2022), 8296.

[8] Z. Zhong, M. Burhan, K. C. Ng, X. Cui, Q. Chen, Low-temperature desalination driven by waste heat of nuclear power plants: A thermo-economic analysis. Desalination, 576 (2024), 117325.

[9] International Atomic Energy Agency, Liquid metal coolants for fast reactors cooled by sodium, lead, and lead-bismuth eutectic. IAEA Nucl. Energy Ser., NP-T-1.6 (2012).

[10] J. Rosales, L. Francois, L. Juan, H. Garcia, Evaluation of the neutron performance of an SMR-PWR with TRISO fuel and partial recharge schemes. IAEA, Vienna (2022).

[11] E. Wieser, K. Clarno, D. Haas, M. E. Webber, The economics of small modular reactors at coal sites: A program-level analysis within the state of Texas. Energy Policy, 202 (2025), 114572.

[12] J. Barták, G. Bruna, G. Cognet, Economics of small modular reactors: Will they make nuclear power more competitive? J. Energy Power Eng., 15 (2021), 193–201.

[13] International Energy Agency, Nuclear Energy Agency, Projected costs of generating electricity. NEA (2020).

[14] E. Shobeiri, F. Genco, D. Hoornweg, A. Tokuhiro, Small modular reactor deployment and obstacles to be overcome. Energies (2023).

[15] Z. Zhong, M. Burhan, K.C. Ng, X. Cui, Q. Chen, Low-temperature desalination driven by waste heat of nuclear power plants: A thermo-economic analysis. Desalination, 576 (2024), 117325.
[16] G. Alonso, E. del Valle, J. R. Ramírez, Desalination in nuclear power plants. Woodhead Publishing, 1st ed. (2020).
[17] A. Al-Othman, N. N. Darwish, M. Qasim, M. Tawalbeh, N. A. Darwish, N. Hilal, Nuclear desalination: A state-of-the-art review. Desalination, 457 (2019), 39–61.
[18] S.U.D. Khan, S.U.D. Khan, S. Haider, A. El-Leathy, U. A. Rana, S.N. Danish, R. Ullah, Development and techno-economic analysis of small modular nuclear reactor and desalination system across Middle East and North Africa region. Desalination, 406 (2017), 51–59.
[19] F. Priego, G. Alonso, E. del Valle, R. Ramirez, Alternatives of steam extraction for desalination purposes using SMART reactor. Desalination, 413 (2017), 199–216.
[20] R. Buzzetti, R.L. Frano, A.S. Cancemi, Feasibility study of desalination plant powered by SMR. Nucl. Eng. Des., 418 (2024), 112897.
[21] A. Asuega, Techno-economic analysis of advanced small modular nuclear reactors. Appl. Energy, 334 (2023), 120669.
[22] G. Alonso, Economic competitiveness of small modular reactors in a net zero policy. Energies, 18 (4) (2025), 922.
[23] N. Van Hee H. Peremans, P. Nimmegeers, Economic potential and barriers of small modular reactors in Europe. Renew. Sustain. Energy Rev., 203 (2024), 114743.
[24] International Atomic Energy Agency, Small modular reactors: Advances in SMR developments. IAEA, Vienna (2024).
[25] F. Reitsma, Small modular reactors and Generation-IV: A short overview. IAEA-ICTP Workshop (2024).
[26] B. Vegel, J.C. Quinn, Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures. Energy Policy, 104 (2017), 41–52.
[27] Z. Zhang, Y. Dong, F. Li, Z. Zhang, H. Wang, X. Huang, X. Huang, H. Li, B. Liu, X. Wu, H. Wang, X. Diao,The Shandong Shidao Bay 200 MWe high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: An engineering and technological innovation. Nucl. Eng. Des., 306 (2016), 1–8.
[28] International Atomic Energy Agency, The applications of research reactors. IAEA, Vienna (1999).
[29] International Atomic Energy Agency, Design and development status of small and medium reactor systems. IAEA, Vienna (1996).
[30] International Atomic Energy Agency, Status of small and medium sized reactor designs. IAEA, Vienna (2012).
[31] D. Ingersoll, Z. Houghton, R. Bromm, Integration of NuScale SMR with desalination technologies. ASME Small Modular Reactors Symposium (2014).
[32] D. Ingersoll, Z. Houghton, R. Bromm, C. Desportes, NuScale small modular reactor for co-generation of electricity and water. Desalination, 340 (2014), 84–93.
[33] International Atomic Energy Agency, On-line conference on the advances in small modular reactor (SMR) design and technology developments. IAEA, Vienna (2020).
[34] International Atomic Energy Agency, Opportunities for cogeneration with nuclear energy. IAEA Nuclear Energy Series, Vienna (2017).
[35] International Atomic Energy Agency, The 17th INPRO dialogue forum on opportunities and challenges in small modular reactor. IAEA (2019).
[36] L. Hall, Nuclear thermal propulsion: Game changing technology for deep space exploration. NASA (2018).
[37] D. Agle, Fueling of NASA's Mars 2020 rover power system begins. NASA (2019).
[38] B. Dunbar,et. al, Space Technology Mission Directorate. NASA (2021).
[39] B. Mignacca, G. Locatelli, Economics and finance of small modular reactors: A systematic review and research agenda. Renew. Sustain. Energy Rev., 118 (2020), 109519.
[40] OECD Nuclear Energy Agency, Small modular reactors: Challenges and opportunities. OECD-NEA (2021).
[41] Nuclear Energy Agency, Small modular reactors: Nuclear energy market potential for near-term deployment. NEA No. 7213 (2016).
[42] U.S. Department of Energy, Benefits of small modular reactors (SMRs). DOE (2025).
[43] G. A. Black, F. Aydogan, C. L. Koerner, Economic viability of light water small modular nuclear reactors: General methodology and vendor data. Renew. Sustain. Energy Rev., 103 (2019), 248–258.
[44] M. K. Rowinski, T.J. White, J. Zhao, Small and medium sized reactors (SMR): A review of technology. Renew. Sustain. Energy Rev., 44 (2015), 643–656.