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A NEW PARADIGM OF ENERGY TRANSITION: SECURITY AND ECONOMIC ASPECTS OF SMALL MODULAR REACTORS

Milica Ćurčić[1] Milan Ljušić[2] Predrag Škobalj[3]

Abstract: Small Modular Reactors (SMRs) represent an innovative and promising technology in nuclear energy, combining economic viability, operational flexibility, and enhanced security standards. This paper explores the economic benefits of SMRs, including lower capital costs, shorter construction timelines, and scalability, making them an attractive option for both developed and developing countries. Additionally, their advanced security features, such as resilience to external threats and reduced risk of nuclear material proliferation, address critical concerns associated with traditional nuclear reactors.

The analysis also considers security challenges and the market acceptance of SMR technology, which remain key hurdles to its widespread adoption. SMRs offer significant potential for contributing to the energy transition by supporting the diversification of energy sources, reducing greenhouse gas emissions, and enhancing energy security, particularly in regions with limited access to reliable power. This paper emphasizes the importance of balancing economic feasibility with robust security measures, offering insights into how SMRs can play a transformative role in achieving sustainable energy goals.

Key words: Small Modular Reactors, nuclear energy, security, economy, energy transition, sustainability

1. INTRODUCTION

Nuclear energy plays a crucial role in addressing the rising global energy demand, driven by population growth and economic expansion, while offering a low-carbon alternative to fossil fuels. Currently contributing around 10.5% to global electricity generation, it is projected to increase to 12% by 2050, making it a key solution for both meeting the world's energy needs and mitigating global warming [1]. Due to the high investment costs of conventional nuclear power plants, there is growing interest in the development and deployment of Small Modular Reactors (SMRs), which offer a more affordable alternative for expanding nuclear programs with lower upfront costs and shorter construction times.

SMRs represent a technological innovation with the potential to reshape the modern energy landscape while meeting the growing demand for sustainable, reliable, and secure energy sources. The International Atomic Energy Agency defines SMRs as "newer generation [nuclear] reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises" [2]. Unlike conventional large nuclear reactors, SMRs offer a distinct advantage due to their smaller physical dimensions, modular design, and the ability to adapt to the specific needs of various energy systems.

The rising interest in SMRs is driven by their unique characteristics, such as the modular construction process, which allows for efficient factory fabrication and on-site assembly, and their flexibility to serve a wide range of applications, including electricity generation, heat production, hydrogen production, and seawater desalination. These reactors are also designed to be scalable, providing the option to gradually increase capacity as demand grows. This scalability not only reduces financial risk but also allows for phased investment, making SMRs an attractive solution for countries with limited resources or smaller energy markets [3]. The combination of lower initial investment costs, shorter construction timelines, and enhanced adaptability makes SMRs a promising technology for meeting the world's evolving energy needs.

[1] PhD, Vinca Institute of Nuclear Science, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa Street 12-14, Belgrade, Serbia, email: milica.curcic@vin.bg.ac.rs

[2] MsC, Vinca Institute of Nuclear Science, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa Street 12-14, Belgrade, Serbia, email: milan.ljusic@vin.bg.ac.rs

[3] PhD, Vinca Institute of Nuclear Science, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa Street 12-14, Belgrade, Serbia, email: p.skobalj@vin.bg.ac.rs

In addition to economic benefits, SMRs are designed with enhanced safety and security features, such as resilience to extreme conditions, reduced risk of severe accidents, and advanced mechanisms to prevent the misuse of nuclear material. These attributes make them particularly appealing to nations seeking to modernize their energy sectors, reduce reliance on fossil fuels, and simultaneously ensure a high level of protection for populations and the environment.

However, despite their significant potential, the implementation of SMRs faces numerous challenges, ranging from complex regulatory requirements and limited market acceptance to public trust issues regarding nuclear technology. One of the key challenges for the assessment of SMR advantages and disadvantages is the lack of empirical information. This paper explores the key economic and security aspects of Small Modular Reactors, highlighting their role in the energy transition. The objective of this study is to provide an analysis that contributes to understanding how balancing economic and security parameters can influence strategic decisions on adopting this innovative technology, with a particular focus on its contribution to energy security, sustainable development, and global carbon emission reduction goals.

2. ECONOMIC VIABILITY AND SCALABILITY OF SMALL MODULAR REACTORS

Small Modular Reactors (SMRs) offer a revolutionary approach to nuclear energy, addressing one of the most significant barriers to the adoption of traditional reactors: high upfront investment and financial risk. With their modular design and smaller physical size, SMRs require substantially lower initial capital costs and have shorter construction timelines compared to conventional nuclear power plants. This makes them particularly appealing to countries with limited financial resources or smaller energy markets. The reduction of investment risk relative to large reactors (LRs) is a key advantage of SMRs. SMRs are characterized by lower upfront investment, reduced capital at risk during construction, and less financial distress than LRs, which significantly decreases investment risk. This risk reduction makes SMRs a more attractive option for utilities or companies that may already be operating several nuclear power plants (NPPs). As a result, the potential to attract investment increases when compared to LRs [4].

Modularization offers significant economic advantages by streamlining the construction process, improving productivity, and reducing costs. By relocating critical construction tasks to a factory setting, it allows for concurrent assembly and construction, resulting in shorter timelines—potentially cutting build times by 25% to 50%. This, in turn, leads to reduced construction costs, with savings of 10% to 20% depending on the project. The use of standardized designs also promotes repeatability, facilitating continuous learning and further cost reductions over multiple builds. Factory-based construction ensures higher quality control and improves constructability, reducing on-site labor and enhancing safety. Additionally, modularization allows for better workforce management by concentrating skilled labor at the factory, minimizing the need for a large labor force at remote or challenging locations [5]. Furthermore, the approach contributes to environmental sustainability by lowering embodied carbon, energy consumption, and water use, adding further economic benefits in terms of regulatory compliance and operational efficiency.

For multi-unit SMRs, the ability to add modules incrementally and begin generating electricity as each unit is completed offers significant financial advantages. This modular approach significantly reduces both upfront investment and capital risk, making the initial costs more manageable and lessening the financial burden on investors. By allowing for phased deployment, the scalability of SMRs enables gradual investments that can be made in alignment with the growing or evolving energy needs of a particular region. This approach ensures that projects are not burdened with large, immediate expenditures, but instead can expand in response to real-time demand and financial availability. Additionally, the incremental nature of expansion means that energy systems can remain flexible, easily adapting to future technological advancements or shifts in market dynamics. As energy needs evolve over time, the ability to scale up capacity incrementally ensures that power generation remains reliable without overextending resources. This adaptability is essential for maintaining energy security while minimizing unnecessary costs. By combining economic feasibility with operational flexibility and efficiency, SMRs position themselves not only as a viable solution for meeting current energy demands but also as a long-term, sustainable, and diversified energy strategy that can respond to future challenges and opportunities.

Additionally, SMRs are designed to allow for the sequential addition of multiple units at the same site. This approach enables the first completed units to begin generating revenue while the construction of subsequent units continues, creating a steady investment flow and boosting investor confidence. By facilitating staggered deployment, this strategy helps utilities better align the growth of nuclear capacity with the increasing demand for energy, reducing the financial burden and making the expansion of nuclear energy infrastructure more manageable [6]. The standardized design of SMRs enables the integration of components, significantly reducing the number of parts required for construction and simplifying assembly processes. This not only enhances production efficiency and repeatability but also lowers maintenance complexity, contributing to improved economic feasibility and operational reliability.

While SMRs offer economic benefits through staggered deployment and sequential module addition, they also face certain challenges. These include constraints related to module transport, which depend on the selected transport mode and distance from the factory, as well as additional design and construction costs for prototype projects and supporting structures. Additionally, modular production requires long-term series production to realize full economic benefits, and licensing challenges may arise due to the need to accommodate smaller, redesigned components and manage international licensing processes for modular units [5,7]. A notable drawback of SMRs is that the technology is still in its developmental stages, with many designs yet to progress beyond prototype or "first-of-a-kind" status. As a result, initial deployment costs remain high, and the full economic benefits of standardized, "end-of-a-kind" production have not yet been realized.

3. ADVANCED SECURITY FEATURES AND THEIR ROLE IN ENERGY SECURITY

As the demand for clean and reliable energy sources increases, the safety and security of energy infrastructure become more critical. SMRs with their innovative design and advanced security features, offer a promising solution to these challenges. Energy security, which involves ensuring a stable, reliable, and sustainable energy supply, depends heavily on the ability to protect nuclear power plants from both operational hazards and external threats. SMRs stand out due to their integration of advanced safety systems, which are designed to minimize the risk of accidents and mitigate potential consequences. These reactors are equipped with cutting-edge safety technologies that enhance their resilience to both internal and external disruptions. Their smaller size and modular construction also contribute to their ability to operate safely in various environments. By addressing the safety concerns associated with traditional nuclear power plants, SMRs provide a pathway to greater energy security, ensuring the continued development and use of nuclear energy in a way that is both secure and sustainable.

One of the key advantages of SMRs is their reliance on passive safety systems, which operate without the need for external power or human intervention. This design greatly enhances the reactor’s safety, ensuring that protective measures are automatically activated in the event of an emergency. By minimizing the possibility of human error, passive safety systems provide a higher level of security during unforeseen situations. Moreover, SMRs are equipped with innovative safety features, designed based on lessons learned from the operation of past nuclear plants. The use of natural circulation and the integration of passive safety mechanisms make these reactors inherently safer and simpler in design. However, it remains essential to thoroughly assess the reliability of these systems in various postulated transient scenarios before deploying them on a large scale. To ensure the effectiveness of passive safety systems, test facilities and best-estimate system codes play a critical role in their evaluation, as well as in the design, certification, and overall assessment of these next-generation reactors [8].

The compact size and modular design of SMRs enhance their security by enabling deployment in more secure, controlled environments. Their smaller physical footprint makes them easier to integrate into existing infrastructure, minimizing exposure to potential safety risks. Moreover, SMRs are small enough to be transportable, making them ideal for deployment in isolated locations where advanced infrastructure or power grids are unavailable [9]. This flexibility allows SMRs to be placed in areas with limited access to resources, while still offering the option to cluster multiple units at a single site to create a scalable, large-capacity power plant that can be expanded as needed.

SMRs are designed to be more resilient to external threats, including natural disasters, cyberattacks, or acts of terrorism. Their compact size allows for underground construction, providing protection from extreme weather events, earthquakes, and electromagnetic pulse (EMP) threats [10]. Additionally, the International Atomic Energy Agency (IAEA) has initiated research projects to advance computer security for SMRs, focusing on integrating robust cybersecurity measures throughout their lifecycle to mitigate risks associated with increased digital automation and remote operations [11]. These design considerations ensure that SMRs maintain operational integrity under various adverse conditions, thereby minimizing risks to the environment and surrounding populations.

Proliferation risks are a critical consideration in the deployment of small modular reactors (SMRs), especially in nuclear energy newcomer (NEN) countries. SMRs are generally designed to enhance proliferation resistance through features such as integrated, sealed cores and extended fuel cycles, which reduce the need for frequent refueling and limit access to nuclear material. Additionally, SMRs inherently use smaller quantities of nuclear material compared to large reactors, further minimizing the potential for diversion. However, the introduction of enrichment or reprocessing (E&R) facilities associated with SMRs could significantly elevate proliferation risks by enabling the production of weapons-usable materials. Research using Bayesian network models and expert surveys indicates that NEN countries with strong commitments to non-proliferation norms and stable security environments face lower proliferation risks [12]. To further mitigate these risks, measures such as implementing spent nuclear fuel (SNF) retrieval systems and ensuring robust international safeguards are critical. These steps, combined with the intrinsic safety and material-limiting design of SMRs, position them as a safer and more secure option for nuclear energy deployment in diverse geopolitical contexts.

The smaller quantities of nuclear fuel utilized in SMRs significantly lower the potential for radiation contamination in the unlikely event of an accident. Unlike large-scale nuclear reactors, which house larger fuel inventories, the compact design and reduced core size of SMRs inherently limit the amount of radioactive material that could be released during a containment breach. This feature is particularly advantageous for deployment in densely populated areas, where the potential consequences of a nuclear incident could affect a large number of people, or in environmentally sensitive regions, where contamination could have long-lasting ecological impacts.

4. CONCLUSION

Small Modular Reactors (SMRs) offer a groundbreaking solution to contemporary energy challenges, balancing economic viability with operational flexibility. Their modular design and scalability help mitigate the financial risks traditionally linked to large-scale nuclear projects, while their ability to scale incrementally ensures they can adapt to changing energy demands. The potential for standardized production and factory-based construction not only reduces costs and enhances quality control but also opens doors for global export opportunities, positioning SMRs as a key player in sustainable energy strategies. While challenges such as high first-of-a-kind costs and developmental obstacles persist, the long-term benefits of SMRs—including enhanced energy security, lower environmental impact, and compatibility with regional infrastructure—solidify their role in the future of nuclear energy. As technological advancements and policy frameworks progress, SMRs are poised to redefine the global energy landscape.

SMRs represent a transformative approach to energy security by integrating innovative safety features with operational flexibility. Their passive safety systems, modular design, and compact size enhance their ability to operate safely and securely across a variety of environments. Equipped with cutting-edge technologies, SMRs are designed to minimize risks associated with both operational hazards and external threats, such as natural disasters or cyberattacks. Additionally, their resilience to external disruptions and the potential for underground construction ensure SMRs can be deployed in secure, controlled locations, contributing to a safer and more reliable energy future.

Although SMRs offer significant advantages in terms of safety, security, and resistance to proliferation, ongoing evaluation of their performance under various scenarios is crucial. Their smaller size and use of reduced quantities of nuclear material lower the potential consequences of an accident, making them a suitable choice for deployment in densely populated or environmentally sensitive areas. However, continued strengthening of international safeguards, cybersecurity measures, and non-proliferation frameworks is vital to mitigating risks. As SMRs continue to evolve and undergo further assessment, they are well-positioned to play a vital role in the sustainable and secure development of nuclear energy worldwide.

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