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Svetoslav Spassov*

THE ROLE OF SMALL MODULAR REACTORS IN THE ENERGY TRANSITION TO DECARBONIZATION

Abstract: The global push to reduce greenhouse gas emissions, while meeting the rising demand for electricity, has led to a growing interest in less polluting energy sources. Small Modular Reactors (SMRs) emerge as a key innovation in nuclear power, offering enhanced safety, transportability, and cost-effectiveness. This paper explores the role of SMRs in advancing decarbonization and strengthening energy security, with a focus on their potential deployment in the EU, including with the aim to achieve climate targets and ensure a stable electricity supply.

The study evaluates various SMR designs using the International Atomic Energy Agency's reactor technology assessment toolkit, considering factors such as safety, economic viability, and regulatory challenges. The findings highlight the critical role of informed decision-making in the successful integration of SMRs into national energy grids, addressing both technical and public perception issues. This paper also underscores the importance of SMRs in creating a sustainable and resilient energy future.

Keywords: nuclear power, small modular reactors, greenhouse gas emissions, energy security, decarbonization, sustainable energy

Introduction

Small Modular Reactors (SMRs) represent a significant advancement in nuclear technology, characterized by their compact size and flexible design. These reactors, with a power output of up to 300 MWe, have the capability to generate approximately 7.2 million kWh per day. In comparison, traditional large-scale nuclear power plants, which often exceed 1,000 MWe, can produce over 24 million kWh per day. SMRs are designed to utilize a variety of coolants, including light water, liquid metal, and molten salt, with some variants, known as Advanced Modular Reactors (AMRs), employing non-light water technologies. This versatility allows SMRs to be adapted for both electricity generation and heat production, offering a modern approach to nuclear fission that prioritizes safety and efficiency. The development and deployment of SMRs are gaining momentum worldwide, driven by the need for innovative and sustainable energy solutions. These reactors are at the forefront of nuclear innovation, incorporating state-of-the-art technology that enhances safety while reducing costs and environmental impact. Many companies and startups are investing in SMR technology, recognizing its potential to revolutionize the energy sector.[1]

* **Svetoslav Spassov** – Assoc. Prof. Dr. at Department of National and Regional Security, University of National and World Economy, Sofia, email: sspassov@unwe.bg

[1] **European Commission**. Small Modular Reactors explained. Available at https://energy.ec.europa.eu/topics/nuclear-energy/small-modular-reactors/small-modular-reactors-explained_en>

Currently, there are over 80 distinct SMR designs in various stages of development across 18 countries. Nations such as the United States, the United Kingdom, Canada, Japan, and South Korea are leading the charge in SMR innovation, each working on unique designs tailored to their specific energy needs and regulatory environments. These developments highlight the growing importance of SMRs in the global energy landscape, as they offer a promising path toward achieving energy security and reducing carbon emissions on a global scale.

SMRS types and their advantages

SMRs provide distinct benefits compared to larger nuclear plants, including reduced initial capital investment, quicker construction timelines, and increased adaptability in deployment locations.[2] These reactors are particularly well-suited for integration into energy hubs, where they can operate in conjunction with renewable energy sources and other energy vectors, such as hydrogen. SMRs are not only designed to generate electricity but are also capable of supplying heat for industrial processes, district heating, and hydrogen production, making them a versatile solution for modern energy needs (European Commission n.d.).

SMRs come in various designs, each with unique characteristics tailored to specific applications and operational needs (Table 1).

Table 1. *Primary types of SMRs*

Type of SMRs		Main features
Light Water Reactors (LWRs):		LWRs are the most common type of SMRs and include Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). These reactors use water as both a coolant and a neutron moderator, offering a proven and widely adopted technology.
Liquid Metal Reactors (LMRs)		LMRs use liquid metal as a coolant, with significant subtypes including Sodium-Cooled Fast Reactors (SFRs) and Lead-Cooled Fast Reactors (LFRs). These reactors are designed for enhanced heat transfer and have the potential to operate at higher temperatures, improving efficiency.
Molten Salt Reactors (MSRs)		MSRs utilize a liquid mixture of salts as both fuel and coolant. This design allows for continuous fuel processing, which reduces nuclear waste and enhances the efficiency of the reactor. MSRs are considered innovative due to their potential to use a variety of fuel types, including thorium.

[2] **Amin, R. et al**. A Review on the Future of SMR Reactors in Nuclear Energy. *Energy and Thermofluids Engineering*, 4, 2024, pp. 17–23.

Gas-Cooled Reactors (GCRs)		GCRs include High-Temperature Gas-Cooled Reactors (HTGRs), Very High-Temperature Reactors (VHTRs), and Pebble Bed Reactors (PBRs). These reactors are known for their high efficiency and operational flexibility, making them suitable for a wide range of industrial applications.

Source: Wang, W. et al. Small Modular Reactors: An Overview of Modeling, Control, Simulation, and Applications. IEEE Access, vol. 12, 2024, pp. 39628–39650. Available at https://doi.org/10.1109/ACCESS.2024.3351220

Some non-light water SMRs are also referred to as Advanced Modular Reactors (AMRs). Leveraging nuclear fission, these reactors are capable of producing both heat and electricity, incorporating the latest technological advancements for improved safety. SMRs are grounded in net-zero technology. Due to their smaller size and capacity, they require less space and cooling water, providing more flexibility in site selection compared to larger nuclear plants. Their modular nature allows for production in series, enabling cost efficiency through economies of scale. Additionally, SMR systems and components can be pre-assembled in factories and transported as modules or even as complete units to their intended locations, significantly reducing installation costs.[3]

It is worth noting also that SMRs offer several advantages over traditional large-scale nuclear reactors, particularly in terms of design and deployment (Table 2).

Table 2. *SMRs' advantages in terms of design and deployment*

SMR's design and deployment features	Advantages
Passive Safety Systems	One of the key benefits of SMRs is their reliance on passive safety systems, which reduces the need for complex active systems such as pumps and external power sources. This design approach minimizes the risk of accidents and enhances overall safety.
Modular Fabrication	SMRs are designed to be manufactured in modules, which can be assembled in a controlled factory environment. This approach not only ensures high-quality standards but also allows for easier transportation and potential underground deployment, increasing security and protection against external threats.
Reduced Cooling Requirements	Reduced Cooling Requirements: Due to their smaller size, SMRs require significantly less cooling water than traditional reactors. This makes them well-suited for deployment in remote or water-scarce regions, where access to large water sources may be limited.

Source: Wang, W. et al. Small Modular Reactors: An Overview of Modeling, Control, Simulation, and Applications. *IEEE Access*, vol. 12, 2024, pp. 39628–39650. Available at https://doi.org/10.1109/ACCESS.2024.3351220

[3] **European Commission**. *Small Modular Reactors explained*, n.d. Available at https://energy.ec.europa.eu/topics/nuclear-energy/small-modular-reactors/small-modular-reactors-explained_en.

Potential contribution of SMRs in decarbonization

SMRs could be a key element of low-carbon energy technology, designed to support the stability of the electric grid, especially as the share of renewable energy sources increases and electricity demand grows. Their compact size and flexibility make SMRs ideal replacements for fossil fuel-fired plants, helping to maintain high-skilled jobs in regions impacted by the closure of these traditional energy facilities. In fact, a very recent example in terms of the importance of nuclear power for sustainable energy solutions, is the signing of long-term agreement between the US's "largest producer of reliable, clean, carbon-free energy" Constellation and Microsoft for power purchase which will restart the TMI Unit 1 nuclear reactor in well-known Three Mile Island nuclear plant in Pennsylvania.[4]

In addition to SMRs, other net-zero technologies are being supported through various legislative measures. These include sustainable alternative fuel technologies, advanced methods for generating energy from nuclear processes with minimal waste, and the development of high-performance fuels specifically designed for use in SMRs and similar systems. Collectively, these innovations are driving the transition to a more sustainable and resilient energy future.[5] By 2020, more than 800 cities globally have pledged to achieve net-zero carbon emissions, demonstrating a growing recognition of the significant role that net-zero carbon initiatives can play in combating climate change. More cities are now setting their sights on achieving net-zero carbon footprints as part of their climate action strategies.[6]

The role of Small Modular Reactors in balancing the electricity grid

Small Modular Reactors (SMRs) play a crucial role in enhancing grid stability by offering flexible load regulation and the capability to operate independently in island mode during grid disconnections. When combined with renewable energy sources and storage systems, SMRs contribute to the creation of balanced local grids that can function as both electricity producers and consumers, adapting to varying energy demands. The flexibility of SMRs extends further through their advanced load-shifting capabilities, allowing for efficient integration with energy storage systems. This adaptability not only supports the overall stability of the grid but also facilitates the seamless incorporation of renewable energy into the energy mix. Moreover, the integration of SMRs with local grids brings significant economic and environmental benefits. By reducing reliance on fossil fuels, SMRs help lower greenhouse gas emissions and enhance energy security, contributing to a more sustainable and resilient energy infrastructure.[7]

IAEA SMR Technology Assessment

The ongoing energy crisis, exacerbated by Russia's invasion of Ukraine, has underscored the critical need for the EU's energy independence. This situation has further strengthened the EU willingness to lead in the development of innovative technologies like Small Modular Reactors (SMRs). Under such circumstances, one can note that a proper technology assessment is more than needed. In fact, the International Atomic Energy Agency (IAEA) launched the so-called SMR Platform to assist countries in the development, deployment, licensing, and oversight of SMR technologies. This platform acts as a central resource, providing essential information to help nations like Brazil and Jordan evaluate and implement SMR technologies effectively.

In addition, both the IAEA and the EU rigorously assess SMRs based on criteria such as safety, performance, economic viability, and environmental impact. These evaluations are crucial in guiding

[4] **Mandler, C.** *Three Mile Island nuclear plant will reopen to power Microsoft data centers*. NPR, 2024 Available at https://www.npr.org/2024/09/20/nx-s1-5120581/three-mile-island-nuclear-power-plant-microsoft-ai

[5] **European Commission**. *Net-Zero Industry Act*. 2023. Available at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en.

[6] **Liu, YL, BJ He**. Evaluating the potential of green roofs in the context of decarbonization of the built environment. In: *IOP Conf. Ser.: Earth Environ. Sci. 1363 012035*, IOP Publishing, 2024, Available at https://iopscience.iop.org/article/10.1088/1755-1315/1363/1/012035.

[7] **Saukh, S. Borysenko**, **A**. Математична модель локальної мережі з АЕС на малих модульних реакторах. *Ядерна та радіаційна безпека,* 2 (94), 2022, https://doi.org/10.32918/nrs.2022.2(94).05.

informed decision-making for the adoption of SMR technologies. The IAEA's Reactor Technology Assessment (RTA) toolkit plays a vital role in determining the feasibility of SMR projects. It focuses on key aspects like energy security, sustainability, and economic viability, ensuring that SMR technologies can meet the demands of a rapidly evolving energy landscape.[8]

The IAEA has refined its Reactor Technology Assessment (RTA) methodology to offer a systematic approach for evaluating nuclear reactor technologies. This updated RTA framework includes 10 key elements (KEs) that serve as the foundation for assessing both user requirements and technical criteria. These key elements provide a structured process to support decision-making, ensuring a comprehensive evaluation of the suitability of various reactor technologies for specific countries or projects.[9]

Regional and international dimensions of smrs research and development

EU actions on SMRs

The European Commission underscores the importance of SMRs. It indicates that they are distinguished by their innovative safety designs, making them particularly well-suited for integrating nuclear technologies into new industrial applications. Their appeal to investors stems from their potential to play a vital role in low-carbon energy systems, contributing to the decarbonization of challenging sectors such as transport, chemicals, steel, and district heating.[10]

The European Union is actively supporting the research and development of SMRs under the Euratom Research and Training Programme (2021–2025). Concerning this, Romania is already progressing with its SMR project, which is aimed to replace a coal plant in Doicesti by 2029, furthering the its national energy security and decarbonization goals.[11] This initiative places a strong emphasis on critical areas such as nuclear safety, security, safeguards, radiation protection, and radioactive waste management, while also focusing on the development of nuclear-related skills across Europe.[12]

What is more, in order to ensure the successful and timely deployment of the first SMR projects by the early 2030s, and to bolster the EU competitive position in the global nuclear market, in February 2024 the European Commission launched the European Industrial Alliance on Small Modular Reactors.[13] It should be noted that this Alliance aims also to create a competitive European SMR industry, which to contribute to placing the EU as a global leader in SMR technology, fostering innovation, strengthening energy security, and contributing to the decarbonization of energy systems across the continent.[14] Therefore, the Alliance has several main objectives, such as developing strategic action plans and technology roadmaps to identify and support the most advanced, safe, and cost-effective SMR technologies; enhancing the European SMR supply chain by addressing existing gaps and providing guidance throughout the project lifecycle, from inception to deployment; analyzing funding opportunities, remove investment barriers, and explore innovative financial models to support SMR development; fostering collaboration between project promoters, European nuclear safety regulators, and EU regulatory authorities; engaging

[8] **IAEA**. The Platform on Small Modular Reactors and their Applications, n.d. Available at https://nucleus.iaea.org/sites/smr/SitePages/HomeSmrPlatform.aspx.

[9] **Saleh, W. et al**. Advancing Small Modular Reactor Technology Assessment in the Czech Republic, Egypt, and Poland. *Science and Technology of Nuclear Installations,* Issue 1, 2023, https://doi.org/10.1155/2023/7002980.

[10] **European Commission**. European Industrial Alliance on SMRs. 2024. Available at https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en

[11] **U.S. Embassy in Romania**. U.S. and Romania Announce Milestone in Small Modular Reactor Project, Advancing Romania One Step Closer to Clean Technology Leadership in the Region, 2024. Available at https://ro.usembassy.gov/pr-07242024/.

[12] **European Commission**, *Euratom research and training programme 2021–2025*. Publications Office of the European Union, 2021. Available at https://data.europa.eu/doi/10.2777/200656.

[13] **European Commission**. *European Industrial Alliance on SMRs*. 2024. Available at https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en

[14] **European Commission**. Small Modular Reactors. 2024a. Available at https://energy.ec.europa.eu/topics/nuclear-energy/small-modular-reactors_en#smrs-at-international-level

potential industrial users to integrate SMRs into their operations; promoting public awareness and engagement; addressing future research on SMRs; collaborating with international actors to boost the EU SMR projects in the global markets (Ibid.).

In addition to this, the EU is actively involved in harmonizing and standardizing regulatory frameworks for SMRs across member states, ensuring that all projects meet the highest standards of safety, security, and environmental compliance (European Commission n.d.).

International projects and initiatives for SMRs deployment

The global push for decarbonization and sustainable energy development has placed SMRs at the forefront of nuclear innovation. Several international projects and initiatives are driving their advancement and deployment, emphasizing SMRs' critical role in meeting energy security and climate goals. In addition, during the "Financing the Tripling of Nuclear Energy" event in New York, 14 major global banks and financial institutions have pledged their support for tripling nuclear energy capacity by 2050, recognizing the critical role that nuclear energy is expected to play in the clean energy transition.[15]

For example, the OECD Nuclear Energy Agency (NEA) plays a significant role in advancing SMR technology across its member countries, including the United States, Canada, and the United Kingdom. These nations are actively supporting SMR development through public-private partnerships, funding research, and facilitating the licensing process.[16]

It is worth noting one particular U.S.-led initiative, namely Project Phoenix, which focuses on partnering with key European and Eurasian countries to replace retired or soon-to-be-retired coal plants with new nuclear energy capacity from SMRs. This initiative is aligned with the highest standards of nuclear security and nonproliferation, while also aiming to retain and retrain the local workforce impacted by the transition from coal to nuclear power. The project emphasizes the need for international collaboration to enhance energy security and promote carbon neutrality.[17] Countries such as Poland, the Czech Republic, Romania, and Ukraine are already actively involved in Project Phoenix, integrating SMRs into their energy strategies to modernize infrastructure and achieve their climate goals. Bulgaria is participating in Project Phoenix, with the University of National and World Economy and "State Enterprise 'Radioactive Waste'' as key partners contributing to research and development efforts to ensure the successful integration of SMRs into the country's energy strategy.

Additionally, Nuclear Expediting the Energy Transition (NEXT), introduced by U.S. Special Presidential Envoy for Climate John Kerry at the Three Seas Initiative Summit in Bucharest in September 2023, offers technical assistance to partner nations through the U.S. Department of State's Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) initiative. NEXT supports both established and emerging nuclear energy countries in developing secure and safe civilian nuclear programs that align with their energy security and climate objectives.[18]

The Net Zero Nuclear Initiative further underscores the crucial role of nuclear energy, particularly SMRs, in achieving global decarbonization goals by 2050, making these reactors a key component in the transition to sustainable energy systems, in both already established nuclear nations and in new ones.[19]

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[15] **World Nuclear Association**. 14 Major Global Banks and Financial Institutions express support to Triple Nuclear Energy by 2050, 2024. Available at https://world-nuclear.org/news-and-media/press-statements/14-major-global-banks-and-financial-institutions-express-support-to-triple-nuclear-energy-by-2050-23-september-2024.

[16] **NEA**. The NEA Small Modular Reactor (SMR) Strategy, n.d. Available at https://www.oecd-nea.org/jcms/pl_26297/the-nea-small-modular-reactor-smr-strategy.

[17] **U.S. Department of State**. Project Phoenix. 2023. Available at https://www.smr-first-program.net/project-phoenix/

[18] **U.S. Department of State**. Special Presidential Envoy for Climate Kerry Announces Project Phoenix Participants and the Nuclear Expediting the Energy Transition (NEXT) Program. 2023. Available at https://www.state.gov/special-presidential-envoy-for-climate-kerry-announces-project-phoenix-participants-and-the-nuclear-expediting-the-energy-transition-next-program/

[19] **Net Nero Nuclear**. About Net Zero Nuclear. 2023. Available at https://netzeronuclear.org/Home/AboutUs.

Developing nuclear security related legislative guarantees in licensing SMRs

The EU and the IAEA, which promotes the safe, secure, and peaceful use of nuclear technology to bolster international peace and security, stress the need for incorporating safety and security considerations from the earliest phases of SMR design.[20] This ensures comprehensive protection against potential threats. For mobile SMRs, which offer enhanced safety and flexibility, stringent security regulations must be tailored to address their specific characteristics effectively (IAEA n.d.).

Kuipers indicates several features that are essential in terms of SMRs deployment and usage.[21] He notes that a graded and risk-informed approach will ensure security measures are tailored to the unique characteristics and reduced power levels of these reactors, while avoiding unnecessary regulatory burdens. At the same time, regulatory frameworks must evolve to address the specific challenges posed by SMRs, including developing threat scenarios that reflect their distinct operational contexts. This includes developing tailored threat scenarios that account for the specific vulnerabilities and operational contexts of SMRs.[22] It is then of great importance ensuring that security measures support, rather than hinder, technological progress, and therefore, a balance between innovation and robust security is needed when it comes to the safe deployment of SMRs in various contexts.[23]

CONCLUSION

Small Modular Reactors are regarded as a transformative force in the ongoing global efforts to achieve decarbonization and enhance energy security. The versatile design and advanced technology of SMRs make them a crucial element in the transition to sustainable energy systems. Their ability to provide reliable and low-carbon energy while being adaptable to various environments underscores their significance in meeting the growing energy demands and stringent climate targets set by the EU and other global entities. This article has highlighted the multiple advantages of SMRs, including their enhanced safety features, cost-effectiveness, and flexibility in deployment. These attributes not only make SMRs a viable replacement for traditional large-scale nuclear reactors but also an essential complement to renewable energy sources. By stabilizing the electric grid and offering solutions for regions transitioning away from fossil fuels, SMRs contribute significantly to reducing greenhouse gas emissions and achieving energy independence. The SMRs integration into national energy strategies, however, requires careful consideration of safety, economic viability, and public perception. The IAEA's reactor technology assessment toolkit provides a critical framework for evaluating these factors, ensuring that SMR projects are developed and deployed in an effective and responsible way. The collaborative efforts within the EU, supported by initiatives like the European SMR Industrial Alliance, further strengthen the position of SMRs as a key component of future energy infrastructure.

In short, SMRs represent not only a technological innovation, but also a strategic asset in the global energy transition. Their successful deployment will depend on informed decision-making, robust regulatory frameworks and continued international cooperation. As the EU member states and other countries around the world embrace SMR technology, it can be stated that it will play an indispensable role in shaping a more sustainable and resilient energy future.

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[22] Ibid., p. 6.

[23] Ibid., p. 12.

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