# A review on Security in Small Modular Reactors and Micro Nuclear Reactors

J.C. GARCIA

Environmental Research Institute IPA

São Paulo, Brazil

Email: address@correspondingauthor.com

R. VENDRAMEL

Nuclear and Energy Research Institute IPEN - CNEN

São Paulo, Brazil

D.A. ANDRADE

Nuclear and Energy Research Institute IPEN - CNEN

São Paulo, Brazil

E.A. RODRIGUES

Nuclear and Energy Research Institute IPEN – CNEN | Environmental Research Institute IPA

São Paulo, Brazil

**Abstract**

Small Modular Reactors (SMRs) are a source for generating electricity and processing heat from nuclear energy, with advantages over large-scale nuclear power plants such as flexibility in location, improved safety, and reduced construction time. SMRs can also be designed as microreactors, aiming at relatively low energy production for industrial facilities, remote off-grid locations, military installations, and areas recovering from natural disasters. Due to their reduced dimensions and the trend towards their large-scale use, additional security and proliferation aspects need to be adequately evaluated. As physical security is a critical consideration for SMRs, especially due need for the protection of facilities, people, and the environment against a variety of potential threats, the objective of this study is to analyze the existing literature, identifying patterns, gaps, and trends to provide insights into the challenges and strategies related to the physical security of these emerging technologies.

## INTRODUCTION

Nuclear power has been an important source of low-carbon energy for decades and its development is considered essential to achieve energy security and climate objectives [1-3]. However, its optimization in the energy framework is complex due to its characteristics involving multiple domains, objectives, time scales, spatial scopes and long time periods; as well as generalized physical elements (nuclear energy chain, non-nuclear energy systems and climate system), social elements (policies and public acceptance) and cyber elements (integration between domains of information acquisition, knowledge extraction and decision support) [1].

The urgency to generate low-carbon energy [4-5] reinforces the role of nuclear energy in providing safe and reliable electricity - throughout 2021, 437 operational nuclear reactors in 32 countries generated around 10% of the global electricity production and more than a quarter of the world's low-carbon production [6].

In addition to nuclear power plants having great potential in non-electric applications (such as district heating, hydrogen production and desalination), the development of advanced and emerging nuclear technology, such as microreactors and small and medium modular reactors (SMRs), increases the potential use of nuclear energy [2,7-8].

SMRs reflect a broad technological spectrum, with more than 80 projects at different stages of development, involving a wide variety of proposals with distinct characteristics in terms of smallness (in power and size), modularity, reactor design, fuel and coolant, refueling and unique features in terms of safety and security [7-9].

Although the concept of very small reactors is not new, with mobile reactors having been commissioned in the 1960s and 1970s, current designs are being considered in the context of changes in fuel types, sensors, electronics, materials and safety systems, with the incorporation of planned and favorable attributes of technological innovations [8].

Despite the heterogeneity of projects under development and the benefits offered compared to traditional nuclear reactors, to date no SMR project has become commercially available [8]. The expansion of these technologies also brings substantial challenges, particularly in the areas of nuclear safety and non-proliferation. Thus, this study aims to review and analyze the security aspects associated with SMRs, identifying patterns, gaps and trends to provide insights into the challenges and strategies related to the physical security of these emerging technologies.

Despite significant progress in the research and development of SRMs, few comprehensive reviews on the development of SRMs have been identified in the literature, according to the research conducted in this study. Thus, as nuclear security is a global priority, especially in a scenario of increased use of advanced technologies, these new challenges need to be rigorously addressed to prevent accidents and avoid the proliferation of nuclear materials, based on clear and effective guidelines for the safe implementation of these technologies. A detailed review of current knowledge and existing gaps is therefore essential to provide practical insights for improving safety policies and practices.

## METHODOLOGY

A systematic literature review was carried out, searching the Web of Science (WoS) scientific database on April 26, 2024, with registration and institutional access by the University of São Paulo. The aim of the search was to select articles that address aspects of security related to SMRs, including microreactors, in order to identify existing patterns, gaps and trends. The search string defined in TABLE 1 was used.

TABLE 1. SEARCH STRING USED IN THE SCIENTIFIC DATABASE WEB OF SCIENCE, ON APRIL 26, 2024.

|  |
| --- |
| **("small modular reactor\*") OR ("SMR\*" AND "nuclear energy") OR (“microreactor\*” OR “micro nuclear reactor\*" OR "micronuclear reactor\*" or “small nuclear reactor\*”) (Topic) and ("security" OR "physical protection" OR "facility protection") (Topic) AND Article OR Early Access OR Review (Document Type)** |

The search identified 53 records of studies published between 2008 and 2024, which covered document types “Article” (N=46) and “Review article” (N=7). The choice of the scientific database WoS as a research source was based on its credibility, interdisciplinary coverage, access to updated and reliable information; and advanced search resources, which provide quality and relevance to the information collected for the review.

After identifying the studies, they were analyzed in their entirety, considering as criteria the availability of the complete article for consultation and its suitability for the research topic. The results were systematized in an Excel spreadsheet, which contains the title and authorship of the study, year of publication, DOI, and two variables to validate each record <complete evaluation> with the values <included/excluded> and < reason for exclusion>, with the values <does not answer the research question/full paper unavailable/paper unavailable in English>.

The analysis was carried out by two members of the research team. Assessments were performed independently to reduce individual bias and increase the reliability of the review. If there was disagreement between the two evaluators, prevailed the result pointed out by the member with the most experience in the subject.

Of the fifty tree articles found, five studies were excluded due to the unavailability of the full paper; two for the unavailability of the paper in English; and 15 because they were unrelated to the research topic. The 31 resulting articles were subjected to a new complete reading, and they were kept for technical analysis (Figure 1).

This work explores the use of VOSviewer for descriptive analyses in the context of research scope. Graphical representations are essential for simplifying complicated datasets because they provide a visual story that improves comprehension and makes for perceptive interpretations. Graphs are an essential tool for descriptive analysis in research, especially in domains that are interdisciplinary and involve both industry and academics. They help researchers identify patterns, relationships, and trends in their data. VOSviewer is a very effective and adaptable tool designed for the visualisation and exploration of large-scale bibliometric and scientometric data, making it stand out among the many graphing techniques available.

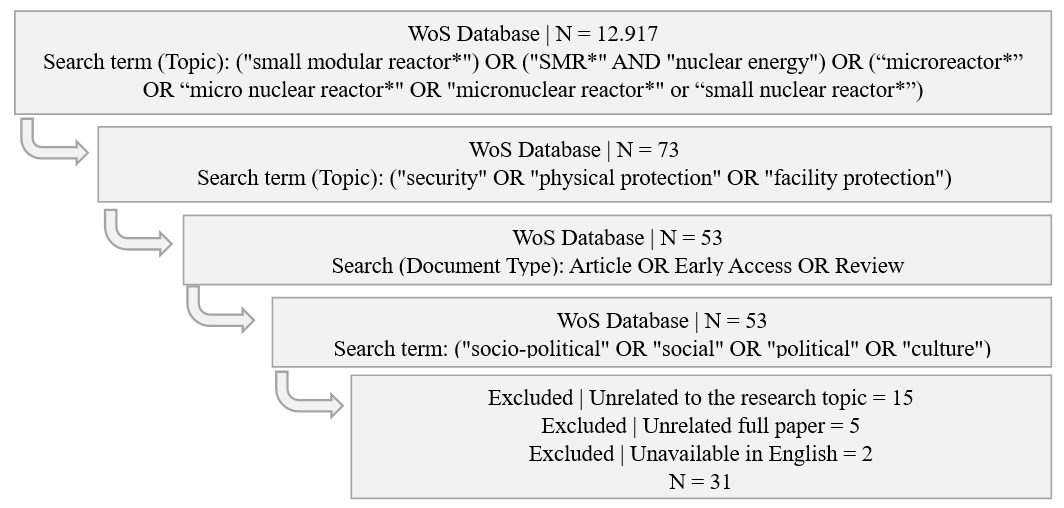


FIG 1. *Diagram applied to the study.*

A TXT and XLS file was exported from the WoS database with complete metadata records of the 31 articles included in the review. For the bibliometric analysis, the keywords described by the authors themselves were selected, out of a total of 105 terms. The conceptually equivalent terms were grouped together (Table 2), resulting in 69 keywords for analysis. This grouping was necessary so that original terms written in different ways could be properly analyzed.

TABLE 2. AUTHORS' KEYWORDS INCORPORATED INTO THE SAME LABEL FOR CO-OCCURRENCE ANALYSIS

|  |  |
| --- | --- |
| **Label** | **Termos incorporados** |
| Advanced nuclear | Advanced nuclear, accident tolerant fuel, advanced nuclear reactors |
| Carbon free energy | Clean electrical network, net-zero, carbon free energy development |
| Climate change | Climate change, global warming, greenhouse gas |
| Energy planning | Energy market assessment, energy modeling, energy scenarios, energy systems |
| Fusion reactor | Fusion reactor, fusion |
| Governance | Governance, politics, regulation, licensing, energy policy |
| Nuclear power | Nuclear power plant, nuclear powerplant, nuclear energy, nuclear power, nuclear |
| Power | Power, electricity |
| Safety | Nuclear safety, criticality safety, safety, safety generation iv, safety-by-design |
| Security | Nuclear security, cybersecurity, nuclear proliferation and security, nonproliferation |
| Site assessment | Site assessment, site selection |
| Small modular reactor | Small modular reactor, small modular reactor deployment, small modular reactors, small modular reactors (smrs), smr, smr plant, micro modular reactor (mmr), microreactors, vehicular microreactor |
| Sociotech perceptions | Sociotechnical imaginaries, public acceptance |

For the keyword co-occurrence analysis, keywords that co-occur more frequently and have a higher link strength were identified. Thus, keywords with a minimum occurrence of two times and a minimum link strength of two were considered, resulting in 13 matches.

In order to analyze and categorize the contribution of each of the 31 studies to the aspects of nuclear security and non-proliferation related to SRMs, a detailed reading of each article was carried out to identify relevant information on: 1) security: security mechanisms and technologies, passive security, cyber protection, monitoring systems and incident response; 2) non-proliferation: strategies to limit access to nuclear material; technologies that hinder the detour of nuclear material; passive safeguards; impact on proliferation resistance. Based on data extraction, each article was categorized into three levels of contribution to the aspects analyzed (Table 3). The data was extracted and the initial categorizations were reviewed and verified by means of AI-supported cross-checks. The table was compiled, listing each article and its respective categorized contributions to nuclear security and non-proliferation.

TABLE 3. CRITERIA FOR CATEGORIZING THE CONTRIBUTION LEVELS OF STUDIES IN SECURITY AND NON-PROLIFERATION RELATED TO SMRs

|  |  |  |
| --- | --- | --- |
| **Contribution Level** | **Criteria considered in the content analysis** | |
| **Security** | **Non-proliferation** |
| High | Innovative technologies, advanced passive security methods, robust cyber protection strategies or highly effective monitoring and response systems | Innovative strategies and technologies that significantly increase proliferation resistance, with effective passive safeguards and methods to limit access to nuclear material |
| Medium | Significant improvements in security, but with less innovation or restricted applicability to certain scenarios | Relevant contribution to non-proliferation, but little innovation |
| Low | Little direct contribution to nuclear security, with a limited focus on security aspects or approaches already known and widely discussed in the literature | Little direct contribution to non-proliferation, with limited focus on non-proliferation resistance strategies or description of established technologies |

## RESULTS AND DISCUSSION

The studies selected for this review cover a wide range of SMR-related topics, including nuclear microreactors, with an emphasis on the areas of security, non-proliferation, technological innovation and regional applications. From 2008 to 2024, research on SMRs has evolved from fundamental studies on design and safety to more complex analyses of integration, regional adoption and advanced technological innovations. While early studies focused on establishing the benefits and potential of SMRs, more recent research addresses specific technical challenges, safety and security improvements and tackling global challenges such as climate change (Table 4).

TABLE 4. STUDIES THAT CONTRIBUTE TO ASPECTS RELATED TO SECURITY IN SRM, SELECTED FOR SYSTEMATIC REVIEW AND BIBLIOMETRIC ANALYSIS

| **Author / Year** | **Ref.** | **Title** |
| --- | --- | --- |
| Smith et al. (2008) | [10] | SSTAR: The US lead-cooled fast reactor (LFR) |
| Kessudes (2012) | [11] | Small Modular Reactors for Enhancing Energy Security in Developing Countries |
| Vujiic et al (2012) | [12] | Small modular reactors: Simpler, safer, cheaper? |
| Petrovic et al. (2012) | [13] | Pioneering Role of IRIS in the Resurgence of Small Modular Reactors |
| Iyer et al. (2014) | [14] | Implications of small modular reactors for climate change mitigation |
| Sovacool et al. (2014) | [15] | Back to the Future: Small Modular Reactors, Nuclear Fantasies, and Symbolic Convergence |
| Black et al. (2015) | [16] | Carbon free energy development and the role of small modular reactors: A review and decision framework for deployment in developing countries |
| Eaves (2016) | [17] | Can North America’s advanced nuclear reactor companies help save the planet? |
| Nian (2017) | [18] | The prospects of small modular reactors in Southeast Asia |
| Kimura & Asano al (2019) | [19] | Ensuring Criticality Safety of SMR Core During Transport Based on Its Temperature Reactivity |
| Merino et al. (2019) | [20] | Environmental Assessment of Energy Scenarios for a Low-Carbon Electrical Network in Chile |
| Thomas (2019) | [21] | Is it the end of the line for Light Water Reactor technology or can China and Russia save the day? |
| Schmid (2020) | [22] | From “Inherently Safe” to “Proliferation Resistant”: New Perspectives on Reactor Designs |
| Carless et al. (2021) | [23] | Estimating nuclear proliferation and security risks in emerging markets using Bayesian Belief Networks |
| Norouzi et al (2021) | [24] | Thermal-hydraulic efficiency of a modular reactor power plant by using the second law of thermodynamic |
| Mitsoboshi & Sagara (2021) | [25] | Effects of U3Si2 fuel and minor actinide doping on fundamental neutronics, nuclear safety, and security of small and medium PWRs in comparison to conventional UO2 fuel |
| Testoni et al. (2021) | [26] | Review of nuclear microreactors: Status, potentialities and challenges |
| Daniel & Kim. (2022) | [27] | A Study on Integrating SMRs into Uganda’s Future Energy System |
| Maio et al. (2022) | [28] | The Contribution of Small Modular Reactors to the Resilience of Power Supply |
| Nian et al (2022) | [29] | Accelerating safe small modular reactor development in Southeast Asia |
| Mathew (2022) | [30] | Nuclear energy: A pathway towards mitigation of global warming |
| Zhang et al. (2022) | [31] | Conceptual design and neutronic analysis of a megawatt-level vehicular microreactor based on TRISO fuel particles and S-CO2 direct power generation |
| Ayodeji et al. (2023) | [32] | Cyber security in the nuclear industry: A closer look at digital control systems, networks and human factors |
| Hayes & Sawers (2023) | [33] | A thermal natural uranium breeder reactor for large and small applications with passive safeguard designs |
| Saleh et al. (2023) | [34] | Advancing Small Modular Reactor Technology Assessment in the Czech Republic, Egypt, and Poland |
| Shobeiri et al. (2023) | [35] | Small Modular Reactor Deployment and Obstacles to Be Overcome |
| Zarebski & Katarzynski (2023) | [36] | Small Modular Reactors (SMRs) as a Solution for Renewable Energy Gaps: Spatial Analysis for Polish Strategy |
| Chmielewska-Smietanko et al. (2024) | [37] | Selected Legal and Safety Aspects of the “Coal-To-Nuclear” Strategy in Poland |
| Defferriere et al (2024) | [38] | Ionic Conduction-Based Polycrystalline Oxide Gamma Ray Detection – Radiation-Ionic Effects |
| Gateau et al. (2024) | [39] | Consequence-based security for microreactors |
| Kansasamy & Brunner (2024) | [40] | Idaho national laboratory to demonstrate collaboration first versus competition to accelerate achieving a secure clean energy future by 2031 |
|  |  |  |

The chronological and textual analysis of the studies reviewed shows a significant increase in scientific production on SMRs between the periods 2008-2020 and 2021-2024, with evidence of a rapidly evolving field (Table 5).

TABLE 5: COMPARISON OF THE CENTRAL THEMES APPROACHED IN SMR STUDIES BETWEEN THE PERIODS OF 2008-2020 AND 2021-2024

| **Period** | **Most frequent central themes** | **Main aspects covered** |
| --- | --- | --- |
| 2008-2020 | Small Modular Reactors (SMRs) | Advantages of SMRS in terms of nuclear safety, efficiency and economic viability. Advanced reactor design and implications for the cost of electricity |
|  | Safety and sustainability | Contribution of SMRs to climate change mitigation and the development of carbon-free energy, with emphasis on nuclear safety aspects |
|  | Reactor technology and design | Studies detail various reactor technologies, with an emphasis on innovation and the safety of advanced designs |
|  | Energy policies and regional implementation | The implementation of SMRs has been explored in different regional contexts (such as ASEAN, Russia and China), considering energy policies and governance practices |
| 2021-2024 | Security and non-proliferation | Significant increase in focus on nuclear security and non-proliferation, reflecting the importance of developing reactors that minimize the risks of nuclear accidents and proliferation |
|  | Energy efficiency and modeling | Efficiency analysis and energy modeling are crucial tools, with studies detailing the performance and resilience metrics of energy systems |
|  | Reactor technology and design | Targeting emerging and innovative technologies, such as microreactors and new types of fuels, with an emphasis on significant advances in design and safety |
|  | Implementation and regulation | The practical implementation of SMRs was discussed at length, addressing issues of licensing, public acceptance and financing, as well as the choice and evaluation of sites |
|  | Energy policies and sustainability | Energy policies and sustainability were central themes, with an emphasis on integrating SMRs into renewable energy and net-zero emissions strategies. |

While in the period 2008-2020 11 publications (35.48%) were identified, with an initial focus on safety, efficiency, economic viability, climate change mitigation and reactor design innovation, between 2021-2024 20 studies (64.52%) were published, with analysis expanding to include safety and non-proliferation, advanced energy modeling and a greater emphasis on energy policies and sustainability. This increase reflects an exponential growth in interest and investment in SMR research, driven by technological advances and contemporary concerns about the sustainable integration of new technologies into the global energy mix.

This work explores the use of VOSviewer for descriptive analyses. By harnessing its capabilities, the aim is to highlight the intricacies of the findings, providing readers with a comprehensive visual representation that complements the textual discussions, including co-authorship networks, co-citation maps, and keyword co-occurrence clusters aiming (Figure 2).

Diagrama

Descrição gerada automaticamente

*FIG 2. Network Graph of co-occurrence between keywords.*

The keyword co-relation analysis identified four clusters. The red cluster - Nuclear power and energy planning (5 items), focuses on discussions about the development of advanced nuclear technologies and their role in generating carbon-free energy. Energy planning is crucial to integrating these new technologies, with an emphasis on the importance of nuclear energy in providing reliable and sustainable electricity. The green cluster - Sustainability and renewable energies (3 items), addresses the relationship between climate change and the development of renewable energies, including nuclear fusion as an emerging technology. The discussion considers how these technologies can contribute to climate change mitigation and the transition to a more sustainable energy system.

The blue cluster - Governance and safety (3 items), highlights the importance of governance and safety, including socio-technical perceptions of public acceptance and regulation of nuclear technologies; these issues are central to ensuring the safe and socially acceptable implementation of SMRs. Finally, the yellow cluster - Safety and Small Modular Reactor (2 items), focuses directly on SMRs and safety aspects. The high frequency and strength of the links indicate that safety is a fundamental concern in discussions about SMRs.

When examining the clusters of co-occurring keywords in a temporal perspective, evidence is found of an increase in the number of publications and the greater diversity and complexity of the issues addressed - security, non-proliferation and sustainability emerge as central themes in the most recent period, with a greater emphasis also on governance and public acceptance, indicating a rapidly evolving and adapting field of research.

The contributions of SMRs as a promising solution to climate change mitigation have been highlighted in several studies [11, 12, 13, 14, 15, 16, 18, 20, 21, 22, 36]. The future viability of light water reactors has been analyzed, with the suggestion that SMRs may be a more suitable alternative for low-carbon nuclear power generation by overcoming the challenges faced by conventional reactors, such as high construction costs and long implementation times [21]. With their modular and safe designs, lower capital investments and shorter construction times, they can be a viable solution for supplying low-carbon energy in isolated and developing regions and can play a significant role in meeting the growing global energy demand while addressing the challenges associated with climate and environmental impact [12].

The role of SMRs in climate mitigation has also been highlighted from new perspectives on reactor designs, which combine inherent safety with proliferation resistance [20] and which can be suitable for diverse applications such as cogeneration and desalination, as well as contributing significantly to climate change mitigation [13]. This analysis is furthered by Iyer et al [14] by using integrated assessment models (GCAM) to demonstrate that SMRs can provide a reliable, low-carbon source, especially when large reactors are not available; their rapid implementation, however, can be limited by social, institutional and behavioral obstacles. The different perspectives and perceptions on SMRs have been addressed in detail as a practical solution to future energy needs and climate change mitigation [15].

The significant potential of SRMs to provide carbon-free energy has also been analyzed for emerging economies, where large nuclear power plants may not be feasible due to high capital costs and infrastructure problems, with an emphasis on lower capital costs, modularity and passive safety features, suitable for integrating with renewable energy sources [16]. As SMRs offer a stable and reliable source of energy, especially in regions where renewable energy capacity is limited, they can help tackle the intermittency of renewable sources by operating continuously regardless of weather conditions; building a diverse and resilient energy mix is essential for reducing greenhouse gas emissions [36]. As SMRs are easier to finance and build, have a lower environmental impact and can be implemented more quickly than large reactors, their implementation in regions with limited infrastructure is highlighted as an alternative for energy security and climate change mitigation [11].

In a regional context, SMRs can play a crucial role in the transition to low-carbon energy in Southeast Asia and position themselves as an effective solution to meet the growing demand for energy while mitigating CO2 emissions [18]. For Chile, the impact of different energy scenarios has been evaluated, with evidence that the inclusion of SMRs in its energy matrix can reduce greenhouse gas emissions and promote low-carbon energy generation; the combination of SMRs with renewable energies can offer an effective solution for achieving stringent climate targets while guaranteeing the country's energy security [20].

Based on a content analysis of the articles in this review, their contributions to nuclear security and non-proliferation were analyzed, categorized and systematized into three value scales.

TABLE 6. LEVEL OF CONTRIBUTION OF STUDIES TO SECURITY AND NON-PROLIFERATION IN SMR

|  |  |  |  |
| --- | --- | --- | --- |
| **Aspects analyzed** | **Level of contribution of the studies** | | |
| **High** | **Medium** | **Low** |
| **Security** | [10, 13, 16, 22, 23, 29, 32, 33, 39, 40] | [11, 12, 14, 15, 17, 18, 19, 24, 25, 26, 27, 28, 31, 34, 35, 36, 37, 38] | [20, 21, 30] |
| **Non-Proliferation** | [10, 13, 14, 16, 18, 22, 23, 25, 29, 32, 33, 36, 39, 40] | [11, 12, 15, 17, 19, 24, 26, 27, 28, 30, 31, 34,35, 37, 38] | [20, 21] |

The studies with a high contribution to the area of nuclear security provide a comprehensive basis for implementing SMRs with enhanced security, combining passive security, cyber protection and collaborative approaches [10, 13, 16, 22-23, 29, 32-33, 39-40]. In addition, the studies categorized as making a high contribution to non-proliferation [10, 13, 14, 16, 18, 22-23, 25, 29, 32-33, 36, 39-40], highlight several advanced technological innovations, such as a reactor with a closed fuel cycle that operates autonomously for 30 years, limiting access to nuclear material [10]; reactor design that combines inherent safety and proliferation resistance, with the use of less attractive fuels and physical barriers [22]; passive safety and modularity [12, 16] and the use of Bayesian networks to model and predict proliferation risks, providing a solid basis for nuclear safety policies [14].

Among SMRs, microreactors, with a potential generally of up to 20 MWe, present attractive characteristics due to their small size and reduced power. With several projects currently under development around the world, these microreactors can be a stand-alone power source or integrated into a grid, providing stable and secure power especially in places where infrastructure is limited [26]. Due to their small size and modularity, they are easier to protect against nuclear proliferation threats can be developed with designs that combine passive security and proliferation resistance [22]; as well as being able to be transported more safely due to their smaller size and reduced complexity [19]. To assess whether the design of the facility meets the safety criteria, consequence-based analysis applied to microreactors was used, with estimates of the consequences on the population of the impact of adverse events that could occur - such as fires, explosions and any human action that could be taken against the reactor [39].

International collaboration is needed to accelerate the development of safe and efficient technologies for clean energy generation [40], whose SMR designs must meet the demands of sustainability, passive safety, proliferation resistance, in-plant production, ease of installation and operation and accessibility, transportability and flexibility in site selection, with a smaller plant footprint and lower investment risk [35]. This progress in SRM technologies requires public investment in research and development, combined with a series of government policies to encourage nuclear energy and strong public acceptance and support from industry [41].

## CONCLUSIONS

This study offers a comprehensive analysis of the security and non-proliferation aspects related to SMRs, with an emphasis on the technological innovations that make these options viable for energy security and climate change mitigation. The systematic literature review revealed that SRMs have significant advantages, such as passive security, modularity and lower operational complexity, which increases their resistance to proliferation, facilitates integration with renewable energy sources, suitable for a variety of applications, such as remote industrial sites and disaster-affected areas.

The implementation of these technologies faces substantial challenges, such as the need for a robust regulatory infrastructure and effective proliferation risk mitigation strategies. International collaborations and the development of policies based on advanced methodologies are crucial to overcome these obstacles. While the implications of these results indicate that SRMS offer promising solutions for energy security and climate mitigation, continued investment in research and development to improve their security and non-proliferation characteristics is essential. Finally, this study recognizes a potential bias due to the selection of articles available only in the WoS database, which may limit the scope of this limitation. Future research should consider a wider range of sources to ensure a more holistic view of the challenges and opportunities associated with SRMs.

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