Hindawi
Science and Technology of Nuclear Installations
Volume 2023, Article ID 7002980, 16 pages
https://doi.org/10.1155/2023/7002980

Research Article

Advancing Small Modular Reactor Technology Assessment in the Czech Republic, Egypt, and Poland

Waad Saleh, Dalibor Kojecky, Edyta Agata Macieja, and Juyoul Kim

Department of NPP Engineering, KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Republic of Korea

Correspondence should be addressed to Juyoul Kim; jykim@kings.ac.kr

Received 6 August 2023; Revised 12 September 2023; Accepted 11 October 2023; Published 21 October 2023

Academic Editor: Leon Cizelj

This paper introduces the utilization of the International Atomic Energy Agency's toolkit for reactor technology assessment (RTA) application to deploy small modular reactors (SMRs) in the Czech Republic, Egypt, and Poland. The increasing demand for clean energy has led to the prominence of small modular reactors (SMRs) in addressing global energy challenges. The successful integration of SMRs into national energy systems necessitates comprehensive evaluations that take into account each country's specific characteristics and energy requirements. RTA application represents significant progress towards innovative nuclear solutions, advancing a cleaner and more resilient energy future plan. The aim of this study is assessing the feasibility and advantages of SMR implementation in these countries, focusing on energy security, emission reduction, and long-term sustainability. Various SMR technologies, including NuScale, SMART, HTR-PM, BWRX-300, SMR-160, and RITM-200, are comparatively analyzed based on safety, scalability, efficiency, and economic viability. The findings reveal that BWRX-300 suits the needs of the Czech Republic and Poland, while RITM-200 is the optimal choice for Egypt. Moreover, NuScale also stands as a strong alternative for all three countries. This article emphasizes the importance of informed discussions and evidence-based decisions, promoting sustainable energy development and global advancements in nuclear technology. By utilizing SMRs, the Czech Republic, Egypt, and Poland can enhance energy security, reduce emissions, and meet rising energy needs sustainably.

1. Introduction

Around 30 countries are currently exploring nuclear power programs, and approximately 20 others have shown interest in adopting nuclear energy to address environmental issues and meet their energy requirements. However, countries' attitudes towards nuclear power might evolve as they assess their energy needs and environmental objectives. Amidst the ongoing global shift towards cleaner energy sources, nuclear power continues to stand out as a significant low-carbon alternative under consideration by multiple countries [1]. As the need for energy increases and environmental concerns become more prominent, the pursuit of abundant, cost-effective, and environmentally sustainable energy technologies is recognized as a paramount objective for humanity in the foreseeable future. In the research conducted by Liu et al. in 2023 [2], it was concluded that advanced nuclear reactor technologies, including fourth-generation nuclear reactors and small modular reactors (SMRs), hold significant promise in terms of improving the economic feasibility, environmental sustainability, safety measures, and adaptability of nuclear energy. These advancements position them as strong candidates for contributing to the goal of achieving carbon neutrality. In a previous study [3], the authors examined the urgent global necessity to shift towards alternative energy sources in numerous countries. The article placed particular emphasis on the expansion of nuclear power technology into new countries. It delved into the increasing interest and eagerness demonstrated by many "newcomer" nations as they evaluated the practicality of incorporating small modular reactor (SMR) designs into their local electricity grids as a more effective and efficient energy solution. As the global transition towards cleaner energy sources continues, nuclear power remains a noteworthy low-carbon option being considered by numerous nations [1]. The International Atomic Energy Agency (IAEA) has taken substantial strides through its "Reactor Technology Assessment (RTA) methodology" program to promote responsible nuclear power program development worldwide. This effort aims to increase awareness of significant nuclear industry advancements, encompassing the establishment of large nuclear power plants in new entrant countries, innovative reactor designs, and technology transfers. Concurrently, efforts to extend the lifespan of existing reactors and explore applications such as small modular reactors (SMRs) have gained traction. To stay aligned with these developments, the latest version of the IAEA's RTA methodology harmoniously incorporates these advancements. It now stands as a comprehensive, contemporary tool for member states to make informed decisions regarding optimal nuclear technology for their specific energy goals [4].

The RTA methodology is essential for the nuclear power infrastructure program, aiding decision-making throughout different phases as follows: prefeasibility study (Phase 1), NPP feasibility study (Phase 2), and bidding (Phase 3). It starts in Phase 1, by identifying technologies aligning with national needs. Capacity building is encouraged even before the prefeasibility study. RTA continues into Phase 2, supporting decision-making during bidding. The level of detail varies based on the program phase. It can be part of Phase 1 preparation, leading to detailed technology evaluations in Phase 2, determining candidate technologies for bidding and selection [5–8].

According to IAEA [9], nuclear power capacity projections have risen in the past decade. Approximately 20.7 GW(e) of new capacity was added, while 8.7 GW(e) was retired. Globally, 437 reactors operated in 32 countries, generating 389.5 GW(e). Around 10 to 12 newcomer countries plan to adopt nuclear power by 2035, considering both large and small reactors. Ensuring strong national nuclear infrastructure is essential for safety and security. A significant technological advancement that has captured the attention of energy planners and policymakers is the expected adoption of small modular reactors (SMRs). This progress has led several newcomer nations to consider integrating SMRs, alongside larger water-cooled reactors, into their plans for increasing capacity in the next three decades. To ensure adherence to nuclear safety, security, and safeguard requirements for both advanced large reactors and SMRs, these countries must establish a robust domestic nuclear power infrastructure. SMRs become cost-competitive with LRs when a country requires around 1,000 GWe of total power [10].

In case of Malaysia, the systems decision process (SDP) of systems engineering, combined with the application of the multiattribute decision-making (MADM) model, is chosen to support complex and multicriteria decision-making processes when selecting the most suitable reactor technology. It is advisable to conduct additional research to establish the most effective approach for conducting reactor technology assessment and selection during the actual development of a reactor selection program [11]. The Alberta government aims to eliminate coal and cut greenhouse gas (GHG) emissions from oil sands operations. Alberta Innovates hired Pacific Northwest National Laboratory (PNNL) to assess the current state of SMR development. They used a two-step analysis method to rank SMR concepts based on full and partial compliance with evaluation criteria [12]. Pacific Northwest National Laboratory (PNNL) and the Massachusetts Institute of Technology (MIT) conducted a study evaluating Gen III + SMRs in the Pacific Northwest. The feasibility study shows competitive deployment between NuScale and BWRX-300 [13]. This report [14] provides surveys on the current status and development plans of small modular reactors (SMRs) and advanced reactors in prominent countries such as the US, UK, Canada, Russia, and China. The surveys focus on policy support for technology development and regulatory schemes within each country. In addition, the surveys offer insights into the planning, feasibility studies, and international cooperation concerning SMR deployment in other countries, such as Indonesia, the Philippines, Poland, the Czech Republic, Estonia, Finland, Jordan, and Kenya. A study was conducted to assess the current state of SMRs and IAEA-assisted desalination projects in the Middle East, North Africa, and various countries worldwide. The potential of the Kingdom of Saudi Arabia (KSA) for adopting nuclear reactors and nuclear reactor desalination was also examined. The study delved into theoretical and computational techniques suitable for nuclear desalination. In addition, the technoeconomic analysis of CAREM and SMART nuclear reactors with cost estimates was discussed, providing valuable insights for estimating different cost scenarios for desalinated water from nuclear reactors [15]. The assessment SMRs using the IAEA Reactor Technology Toolkit was conducted for Ghana, evaluating five different types of reactors [16].

This study focuses on the deployment of small modular reactors (SMRs), including NuScale, SMART, HTR-PM, BWRX-300, SMR-160, and RITM-200, for electricity generation and nonelectric applications. The methodology considers the integration of these reactors with other energy resources for the Czech Republic, Egypt, and Poland. The SMRs that have been chosen for consideration in these countries possess the capability to be constructed there, primarily due to the fact that the companies responsible for their design have already developed suggestions for cooperation with these respective nations. The decision to focus on the Czech Republic, Egypt, and Poland in this RTA is influenced by the national backgrounds of the authors and the fact that all three countries are actively exploring the integration of SMRs into their national energy strategies. Moreover, they are currently engaged in the process of identifying the most appropriate reactor design for their energy needs [17–19]. The study provides a comprehensive framework to guide them through the necessary steps and considerations for establishing the required infrastructure successfully. By combining the RTA methodology with the guidance from the IAEA Milestones publication, these countries can make well-informed decisions regarding the most suitable nuclear technologies. This will ensure the successful development and seamless integration of nuclear power projects into their national energy plans, addressing both electricity generation and nonelectric applications.

2. Materials and Methods

As the world faces the urgent need to address and adapt to the impacts of global climate change, nuclear power is frequently suggested as a viable low-carbon energy source. It is considered a potential solution to reduce greenhouse gas emissions and combat climate change. However, the difficulties associated with financing nuclear power projects are often underestimated, particularly for low- and middle-income countries. Nuclear power projects require substantial initial investments, and the complexities and high costs involved in constructing nuclear power plants can be significant barriers, especially for countries with limited financial resources. In addition, there are ongoing operational and maintenance expenses that need to be considered. Despite the potential benefits of nuclear power in the fight against climate change, it is crucial to acknowledge the financial obstacles and work towards finding solutions that enable wider access to nuclear energy for countries striving to transition to low-carbon sources of electricity generation [20].

2.1. RTA Methodology. The process of applying the RTA (Reactor Technology Assessment) involves several stages to assess the suitability of small modular reactors (SMRs) for different countries' nuclear power programs. The steps in this process are shown in Figure 1 as follows. In the initial stage, we assess the country's policies and regulations related to nuclear energy and their alignment with SMR deployment. We consider public perception and acceptance of nuclear energy and SMR technology in each country. In the second stage, determining the feasibility of deploying small modular reactors (SMRs) in the Czech Republic, Egypt, and Poland, several key criteria need to be evaluated. These criteria include 10 key elements which are illustrated in Figure 2, assessing the countries' current and future electricity demand, evaluating their energy security and vulnerability to supply disruptions from imported energy sources, measuring the potential environmental impact and greenhouse gas emission reductions achieved through SMR adoption, analyzing the economic viability and cost-effectiveness of SMRs compared to other energy sources, considering safety and security implications associated with SMR technology integration, evaluating the readiness of existing infrastructure to support SMR deployment and operation, assessing the alignment of policies and regulations related to nuclear energy with SMR deployment, and taking into account the public perception and acceptance of nuclear energy and SMR technology in each country. During the third stage of the study, comprehensive data on NuScale, SMART, HTR-PM, BWRX-300, SMR-160, and RITM-200 are gathered to encompass all essential criteria and elements. Finally, we evaluate each SMR technology based on the significance of each criterion using a rating scale. RTA tool multiplies the score by its corresponding weightage to calculate the weighted score for each technology, and then comparison of the weighted scores is carried out to determine the most suitable option for each country.

The IAEA has refined the reactor technology assessment (RTA) methodology to provide a structured approach for decision-making when considering nuclear reactor technologies. The refined RTA methodology consists of 10 key elements (KEs) that serve as the basis for evaluating user and technical criteria. These KEs help guide the decision-making process and provide a comprehensive framework to assess the suitability of different reactor technologies for specific countries or projects. The RTA methodology consists of 10 KEs, each essential for evaluating the suitability of SMRs for specific nuclear power projects. The importance of these KEs varies, and they are defined by specific KTs that provide detailed criteria for assessment. The following is a summary of each KE:

KE1. Site-Specific Parameters: this element focuses on site-related factors and has medium importance for SMRs due to their lower land and water resource requirements.

KE2. Nuclear Energy Production: this element encompasses all aspects of nuclear energy production, including fuel processing and reactor operation. It holds high importance, significantly impacting reactor operation and operating costs.

KE3. Safety and Radiation Protection: This element emphasizes on achieving proper operating conditions and preventing accidents to protect workers, the public, and the environment from radiation hazards. It holds the highest KE contribution level.

KE4. Nuclear Design Impact on Site Parameters: this element considers site-specific parameters in relation to nuclear design, with a greater focus on SMRs.

KE5. Balance of Plant and Grid Interface: this element describes the interface between the balance of plant (BOP), site, and grid system, crucial for safe, economic, and reliable operation.

KE6. Balance of Plant and Nonelectric Production System: this element focuses on the interface among BOP design, site, and nonelectric production systems, considering capacity and compatibility with the country's requirements.

KE7. Safeguards and Security: This element addresses safeguards, prevention, detection, and response to theft, sabotage, and illegal access. It holds high importance for SMR designs.

KE8. Technology Experience: this element assesses the level of experience through operation and demonstrates the capabilities of SMR technologies, particularly for first-of-a-kind (FOAK) SMR designs.

KE9. Technology Delivery: this element evaluates the ability of the technology holder to deliver SMRs as specified within schedule and cost.

KE10. NPP Capital Costs: this element focuses on site-specific nuclear power plant capital costs, which can

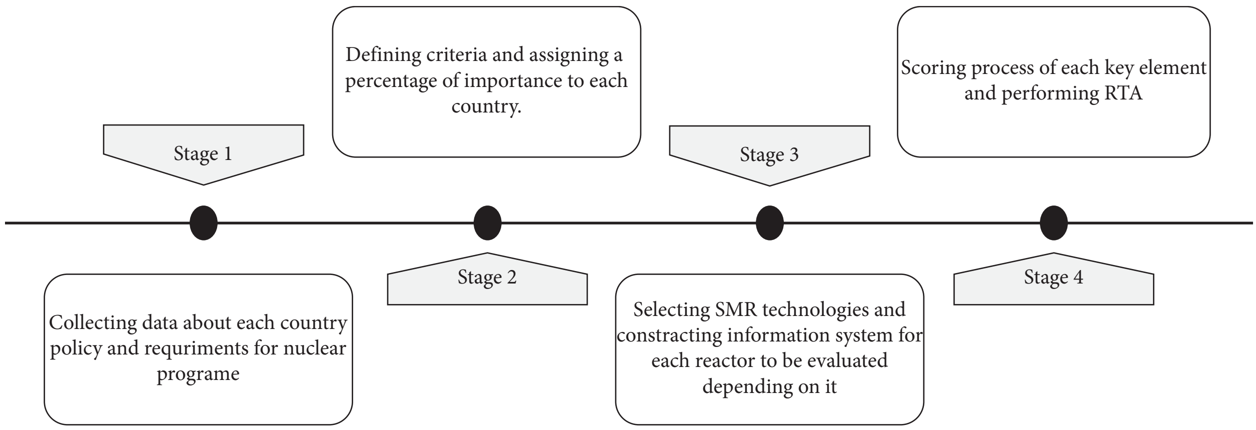


Figure 1: Reactor technology assessment's study plan.

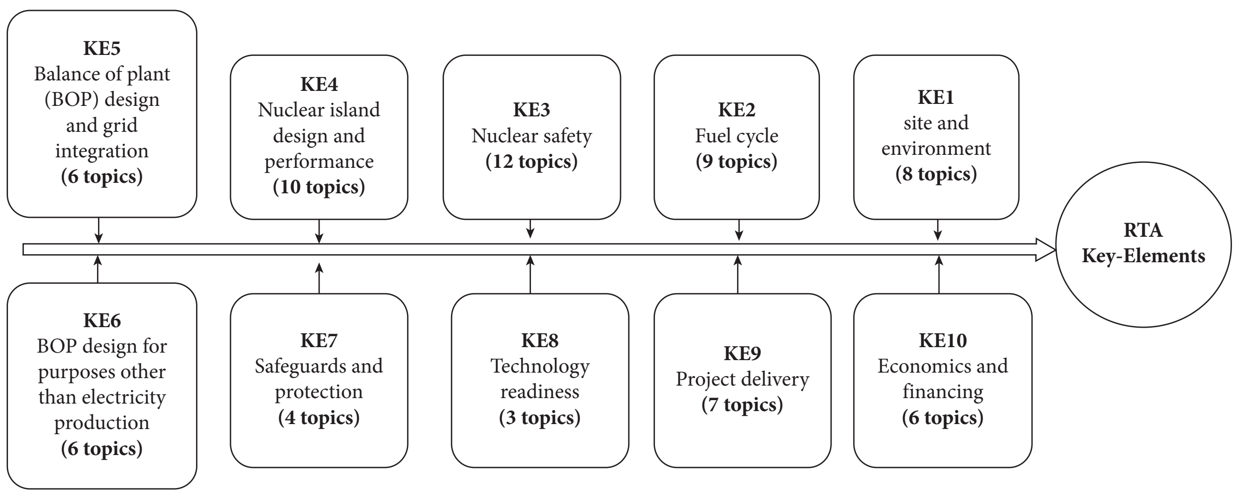


Figure 2: Key elements of RTA.

vary based on material quantities, labor, equipment, etc. Economic data for SMR technology are still developing due to limited operational experience.

The RTA methodology allows for a comprehensive assessment of SMR technologies tailored to individual countries and projects, with the flexibility to assign varying levels of importance to specific KTs within each KE [4].

2.2. SMR Technologies. Small modular reactors (SMRs) are a generation of advanced nuclear reactors designed in a way that allows for modular manufacturing in a factory and subsequent transportation of these modules to the construction site. This approach offers a higher level of predictability in reducing construction expenses and timeframes. It achieves this by leveraging manufacturing efficiencies and minimizing the need for extensive on-site work [21]. While factory manufacturing of SMRs involves handling fewer components, thereby improving worker safety on-site and potentially leading to cost savings in terms of labour and construction, it is important to note that the costs associated with the supply chain can be substantial. The transportation, logistics, and coordination required for moving modular components to the construction site can contribute to these supply chain expenses. Therefore, while there are advantages in terms of safety and construction efficiency, careful planning and management of the supply chain are essential to ensure the overall cost-effectiveness of SMR projects [22]. In addition, unlike larger reactors, SMR designs are characterized by their compact nature. This compactness is achieved by integrating numerous components such as reactor coolant pumps, pressurizers, and steam generators into a single-reactor vessel. This design approach results in a more streamlined and efficient utilization of space within the reactor system. Modularization plays a vital role in the engineering development of SMRs, offering several advantages. It brings about cost savings through reduced initial capital investment, allows for scalability, and provides flexibility in choosing locations that may not accommodate larger conventional reactors. Moreover, the concept of modularity, where a plant is designed by assembling similar reactors of lower capacity, brings about additional benefits such as cositing economies, enabling cogeneration for load-following in nuclear power plants (NPPs), facilitating quicker learning, and enhancing operational flexibility. In addition, during the manufacturing and assembly stages, modularization enables functional and system testing, leading to a higher degree of parallelism and consequently shorter project timelines. This approach often draws upon established techniques from industries such as shipbuilding, aircraft manufacturing, and the automotive sector [23–26]. A significant challenge in the deployment of these innovative SMR designs is the ability of individual national regulatory bodies to assess and approve them. The shift from on-site construction to factory-based manufacturing is a core principle of modularization. This means that many of the tasks related to licensing could potentially be carried out at one or more factory sites. Consequently, the primary concern for regulatory bodies would be ensuring the traceability of components throughout the entire supply chain. The IAEA's Nuclear Power Technology Development Section has identified significant challenges in the licensing and design certification of SMRs. These challenges encompass a wide range of issues, including unique engineering aspects, the feasibility of deploying multiple modules at a single site, ensuring proliferation resistance, addressing security concerns, determining appropriate control room staffing, establishing effective emergency planning zones, managing technology transfer, and safeguarding proprietary design information. These complexities underscore the need for comprehensive regulatory frameworks and international cooperation to navigate the unique characteristics and regulatory demands associated with SMRs [21, 27, 28].

SMR design and engineering are typically finalized once they have undergone regulatory reviews and have received permission for construction within a given nation. As of now, only a select few SMR designs have achieved regulatory clearance or are currently under construction. These designs include the American NuScale and SMR-160, the Korean SMART, the Russian RITM-200, as well as the BWRX-300 design from Japan and the USA. This regulatory approval highlights their progress towards becoming operational and contributing to the global nuclear energy landscape [21, 28]. The comparison study using the RTA is performed on five different SMR technology designs. For the Czech Republic and Poland, these five SMRs are as follows: NuScale (R#1), SMART (R#2), HTR-PM (R#3), BWRX-300 (R#4), and SMR-160 (R#5). For Egypt, the first four SMRs are the same, but the last one is replaced with RITM-200 (R#5*). Table 1 contains basic information about these six reactor types.

2.3. Summary of the Energy Sector in the Analyzed Countries

2.3.1. The Czech Republic. The energy landscape in the Czech Republic reveals a promising mix of electricity sources. Historically, the country's electricity generation heavily relied on coal and nuclear power plants, supported by coal and uranium mining, with coal-fired power plants being the leading contributor, representing 41 percent of total generation in 2021. Not far behind, nuclear power played a significant role, contributing 36 percent to the overall electricity generated during the same period. Renewable energy sources also demonstrated their growing importance, accounting for 14 percent of the total electricity generation in 2021 [30]. The Czech Republic has consistently held a position as a net exporter of electricity over the past two decades, and over the past decade, the gross-electricity generation has maintained a relatively stable level, fluctuating around an annual average of 86 TWh. As shown in Figure 3, according to the Czech Ministry of Industry and Trade, the expected electricity production and consumption for the National Plan (2021–2030) and beyond (up to 2040) show that nuclear power plants are projected to contribute 46–58% of electricity production by 2040 [31]. Currently, the Czech Republic has two distinct nuclear power plant sites. In the 1970s, the Dukovany site saw the construction of four VVER-440/V213 reactors, all completed and operational between 1985 and 1987. Another two VVER-1000/V320 units were completed and operational by 2003 at the Temelin site. As of now, the Czech Republic operates six reactors. The Dukovany site hosts four units with a total installed power of 2040 MWe, while the Temelin site has two units with a total installed power of 2110 MW [32, 33]. CEZ, the company that operates both the nuclear power plants in the Czech Republic, has allocated a specific area within the Temelin Nuclear Power Plant site for the possible construction of the country's first small modular reactor in the future. Temelin, located in southern Bohemia, possesses several notable advantages as a proven nuclear site [17]. CEZ aims to finalize the selection of technology for the Czech Republic's inaugural small modular nuclear reactor within the year 2024. The company is actively collaborating with seven firms engaged in the development of this cutting-edge technology. CEZ has signed memorandum of understanding (MOU) with NuScale, GE Hitachi, Rolls Royce, EdF, KHNP, and Holtec. CEZ also established cooperation on the construction of small modular reactors with Westinghouse. Anticipated plans involve the construction of the first modular reactor at the Temelin site by the year 2032 [17].

2.3.2. Egypt. Egypt is a developing nation with a rapidly expanding population of approximately 102 million as of January 2022. Nearly 95% of the population resides in the Nile Valley and Delta regions. The country's ambitious economic growth prospects, coupled with its demographics, present significant challenges in managing natural resources, employment, infrastructure, education, and healthcare [34]. Since late 2014, President Abdel Fattah El-Sisi has introduced a new strategy to strengthen the energy sector in response to increasing energy demand. The strategy includes expanding energy infrastructure, increasing energy production units, exploring additional energy resources, and encouraging the adoption of renewable energy sources. Moreover, Egypt has future plans to integrate nuclear energy into its energy mix [35]. In 2019, Egypt contributed 0.73% of global greenhouse gas emissions. Its per capita emissions of 3.5 tonnes of CO_2 equivalent were lower than the EU average and the global average [36]. The energy sector in Egypt collaborated with the European Union on a study to determine the optimal technical and economic energy production mix until 2035. The project aimed to support

Table 1: SMR reactors considered in the study [21, 29].

Reactor	NuScale	SMART	HTR-PM	BWRX-300	SMR-160	RITM-200
Designer	NuScale power LLC	KAERI	INET Tsinghua University	GE Hitachi Nuclear Energy	Holtec International	Rosatom
Country	USA	South Korea	China	USA/Japan	USA	Russia
Type	Integral PWR	Integral PWR	HTGR	BWR	PWR	Integral PWR
Power	77 MWe	107 MWe	210 MWe	300 MWe	160 MWe	50 MWe
Status	Received US NRC certification	Standard design approval received	In operation	Prelicensing	Phase 1 in progress	Detail design
Countries selected for RTA	the Czech Republic Egypt Poland	the Czech Republic Egypt Poland	the Czech Republic Egypt Poland	the Czech Republic Egypt Poland	the Czech Republic Poland	Egypt

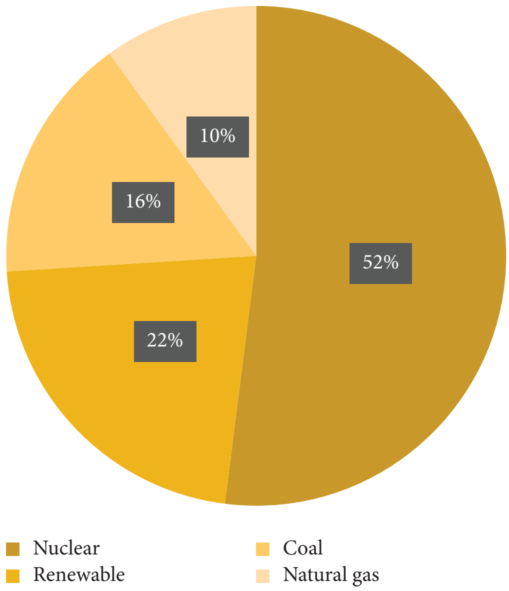


FIGURE 3: Electricity production plan for the Czech Republic by 2040 [31].

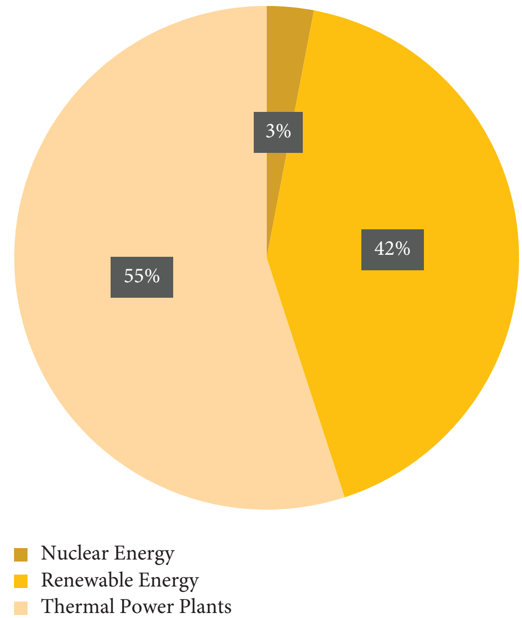


FIGURE 4: Electricity production scenario for Egypt by 2035 [37].

a sustainable and integrated energy strategy for Egypt. The study involved various scenarios, evaluating the impact of different rates of renewable energy integration into the electricity generation mix from both technical and economic perspectives. The Egyptian Energy Strategy until 2035 was approved by the Supreme Council of Energy in October 2016. Figure 4 illustrates the Egyptian scenario by 2035 [37]. In the past, Egypt had plans for nuclear power plants, but they were abandoned after the Chernobyl accident. However, in recent years, Egypt has revived its nuclear energy plans and signed agreements with Russia, China, and South Korea for nuclear cooperation. Construction has started on the first units at the El Dabaa site, with plans for more units in the future [38]. The success of the first nuclear power plant (NPP) in Egypt is crucial as it will pave the way for an ambitious program to construct more NPPs, ensuring sufficient energy generation to meet future peak demand. The Egyptian government's determination to develop a competitive industrial infrastructure will support the nuclear program and ensure the stability of these projects. The plan is to build six additional NPPs if the first project proves to be successful [35]. Dr. Amjad El-Wakeel, chairman of the Egyptian Nuclear Power Plants Authority (NPPA), has identified Al-Nigela 1 and 2 sites in Matrouh Governorate as promising locations for future nuclear projects. Feasibility studies, building upon previous work by Worley Parsons, have been conducted for these sites. Dr. El-Wakeel highlighted their suitability for small modular reactors (SMRs), which offer faster implementation, cost efficiency, and flexible capacity ranging from 10 MW to 400 MW. The NPPA is exploring SMR technologies from the US, South Korea, and Russia. The initial phase of the Egyptian nuclear project will focus on constructing the first four units at El Dabaa, with the potential for eight units in total. The Al-Nigela sites are also considered ideal for housing SMR units, according to the NPPA chairman [18].

2.3.3. Poland. As of 2020, fossil fuels remain the majority of Poland's energy supply (85% of the total energy supply), with coal supplying the majority of it (40%), followed by oil (28%), and natural gas (17%). In Poland, coal's contribution to energy system declined from 2010 to 2020. Polish coal production is also declining, and Poland has been the net importer of coal since 2017 [39].

The adoption of the "2020 Climate and Energy Package" and the "2030 Climate Target Plan" [40, 41] by the European Union has accelerated the need for Poland's energy sector to undergo a significant transformation. In Poland, the main documents defining its energy and climate policies are the National Energy and Climate Plan (NERCP) [42]. A document that must be adopted by all EU member states by 2019 and the National Energy Policy until 2040 (EPP2040) [43], document which was adopted in February 2021. Poland has a wide range of energy and climate targets for 2030 as part of its national and EU legislation, and Poland's energy-intensive industries and electricity generation are governed by the Emissions Trading System (ETS). A key objective of Poland's National Energy and Climate Plan (NECP) adopted in 2019 is to help reach the EU's 2030 targets for non-ETS GHG emissions, renewable energy, and energy efficiency. Although Poland has no commercial nuclear power plants in operation, the introduction of nuclear power is an essential part of EPP2040 and is detailed in the Polish Nuclear Power Programme [44]. In the past, the Polish government had considered a project for constructing a commercial nuclear power plant but abandoned it following a Council of Ministers decision in 1990, influenced by public concerns after the Chernobyl accident. Poland, however, has experience in the operation of research reactors. National Centre for Nuclear Research operates the multipurpose reactor MARIA. For over 35 years, this organization also operated the research reactor Ewa, which was decommissioned in 1995, and as a result, Poland has developed domestic capabilities in planning, regulating, and operating nuclear facilities, as well as managing radioactive waste. Moreover, the NCBJ worked on the conceptual design of the Polish high-temperature research reactor named as HTGR-POLA. In June 2023, the design was finalized by the Department of Nuclear Energy and Environmental Analysis team. This helium-cooled reactor, with a height of 12.3 meters and 4.1 meters of diameter, is set to generate 30 MW of thermal power. The prismatic-type core will consist of hexagonal blocks, be moderate with graphite, and use TRISO-type fuel with 8–12% enrichment. The primary-forced circulation helium cooling circuit will operate at a pressure of 6 MPa, with an outlet temperature of 750°C and an inlet temperature of 325°C. The reactor will have both passive and active safety measures and is designed to have a lifespan of 60 years. The HTGR-POLA project was developed in collaboration with the Japan Atomic Energy Agency (JAEA), which possesses its own high-temperature test reactor (HTTR), a 30 MWt prototype graphite-moderated helium gas-cooled reactor [45]. There are ambitious plans for Poland to embrace nuclear energy. By 2033, the government aims to have the first reactor up and running with a capacity of 1.6 GW and six reactors with a total capacity of 6–9 GW by 2043. It is estimated that by 2040, nuclear energy could generate 23% of electricity in Poland as shown in Figure 5 [46]. According to the established timetable, the commencement of construction for the initial nuclear power plant is scheduled for 2026. Following this, additional units will be introduced at intervals of approximately two to three years, in alignment with the planned timeline. Westinghouse's AP1000 was chosen for the first reactor at the Lubiatowo-Kopalino site [47]. Meanwhile, Korea Hydro & Nuclear Power has partnered with Polish companies ZE PAK and Polska Grupa Energetyczna to build a nuclear power plant in Pątnów [48].

Various initiatives are also underway to bring SMRs to Poland. In December 2021, GE Hitachi, BWXT Canada, and Synthos Green Energy (SGE) signed a letter of intent to cooperate in deploying BWRX-300 SMRs in Poland. Orlen Synthos Green Energy, a joint venture between chemical producers SGE and PKN Orlen, submitted an application to Poland's National Atomic Energy Agency on 8th July, 2022 for the assessment of GE Hitachi Nuclear Energy's BWRX-300, for which it holds the exclusive right in Poland. GE Hitachi Nuclear Energy's BWRX-300 small modular reactor (SMR) technology is compliant with the Polish nuclear safety and radiological protection standards, the president of the National Atomic Energy Agency (Państwowa Agencja Atomistyki, PAA) said in a general opinion. BWRX-300 small modular reactor technology was found to be compliant with the Polish nuclear safety and radiological protection standards as the president of the NAEA said in a general opinion [49]. A similar application for NuScale's VOYGR SMR was submitted the same year by copper and silver producer KGHM Polska Miedz SA. The aim was to have at least 10 reactors operational by 2030. The plan to construct a power plant based on NuScale Power's small modular reactor has been approved by the Ministry of Climate and Environment [50]. SMRs are seen as complementary to the state's plans to build large reactors, as the Polish government anticipates a significant demand for both nuclear technologies due to decarbonisation and electrification of the energy sector. Moreover, after 2030, Poland will have to decommission a significant number of coal plants that serve industrial and district heating applications. By retrofitting the existing coal plants with SMRs, especially those that have under 20 operation years or have been upgraded recently, the risk of stranded assets can also be reduced. As it has been mentioned previously, the Polish private sector is increasingly interested in small nuclear reactors (SMRs). Several companies from the chemical, petrochemical, and mining industries have signed collaboration agreements with vendors in order to evaluate how SMRs might help them decarbonize their energy needs [19].

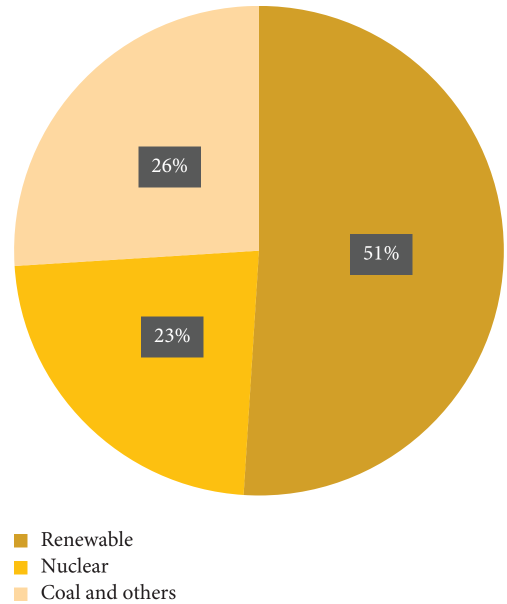


Figure 5: Electricity production scenario for Poland by 2040 [46].

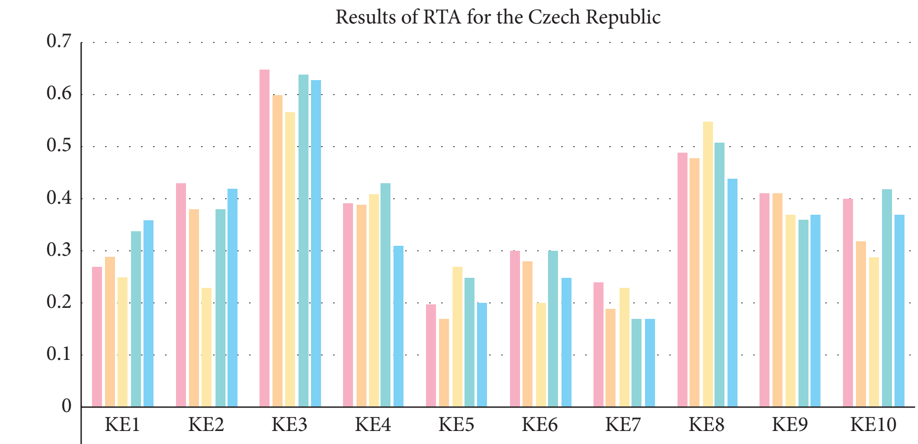
2.4. Grading. The grading process assessed 73 key topics for each of the five SMR designs in three countries, resulting in a total of 365 grading cases for each country. Detailed rationales for each grading were developed, and extensive research informed the final grading. The paper gives a brief overview of the procedure for multiple topics, but detailed explanations could not be included due to the large number of topics. The grading process showed similar reasoning for the Czech Republic and Poland, especially when their needs aligned due to their geographic and cultural proximity. As a result, some topics received comparable grades in both countries. In addition, certain topics had almost identical grading rationales across all three countries (the Czech Republic, Egypt, and Poland) because of shared interests and commonalities, leading to parallel grading assessments. A complete grading process is available upon request. Detailed explanations for the selected key topics' grading in each country are presented as follows.

In the Czech Republic, seismic activity is minimal and the Temelin NPP area exhibits a low seismic risk. A seismic design with a peak ground acceleration (PGA) of 0.1 g, which is used for the two currently operated NPPs, received a score of 3. A design with a PGA of 0.2 g gets a score of 4, and a design with a PGA of 0.3 g or higher is given a score of 5. Most SMR designs evaluated for the Czech Republic received a score of 5 due to their higher seismicity values (0.3 g or 0.5 g), except for HTR-PM, which scored 4 with a seismicity value of 0.2 g [51]. In Egypt, the El Daba area, similar to EL Negaila, is evaluated for the seismic risk. The highest PGA values, reaching up to 0.15 g, are observed for a 400-year return period. SMRs intended for deployment in Egypt should have a seismic design between 0.2 g and 0.3 g, which is assigned a score of 4, indicating favorable seismic resilience [52]. In Poland, specific sites for planned SMRs have not been selected yet and the country experiences low seismicity. Therefore, site seismicity is currently not a significant concern, and the grading follows the same rationale as in the Czech Republic case [51]. Evaluating site-specific capital costs for SMRs is crucial for the Czech Republic, Egypt, and Poland, but it poses challenges due to limited actual experience with these technologies. All three countries consider capital costs a significant factor in their nuclear energy projects and evaluate SMR designs based on several criteria, including optimization, estimation, control, supply chain identification, experience feedback, and accurate cost assessment and management. However, since SMR technologies are still in the developmental stage, precise economic data based on actual experience are currently unavailable, making detailed assessments more challenging compared to large conventional reactors. Nonetheless, it is believed that the economics of SMRs may be influenced by their smaller size [10]. In the Czech Republic, capital costs are the main expenses for nuclear energy, but no specific figures have been specified [53]. In case of Egypt, it needs to increase natural gas prices to $15–$20 per mm BTU to ensure the economic viability and competitiveness of its nuclear project [54]. In Poland, capital costs are a significant factor in nuclear energy and the initial investment for SMRs is relatively lower compared to large reactors [55]. The scoring for SMR designs considers optimization, estimation, and control of capital costs, as well as the level of experience and feedback. For the Czech Republic, Egypt, and Poland, the capital cost is weighted at 40%, 30%, and 30%, respectively, among the key elements' factors in economics and financing.

3. Results and Discussion

3.1. Czech Republic. Based on the RTA conducted for the Czech Republic, the results (Figures 6 and 7 and Table 2) indicate that BWRX-300 is the most suitable technology to meet the country's needs. This reactor technology demonstrated remarkable reliability and high standards in factors crucial for the Czech Republic, particularly in the area of district heating. NuScale SMR closely trailed behind BWRX-300 and received commendable ratings across all 10 key elements. In terms of KE 3, fuel cycle, NuScale SMR obtained the highest number of points, although all reactor designs earned very high ratings in this key element due to their excellent safety features. In the third place was SMR-160, mainly due to its inconsistency. Based on the RTA results, this reactor is the best fit for the Temelin SMR site based on key element 1, site and environment. However, SMR-160 received a low number of points in many key elements, such as KE 4, nuclear island design and performance, as well as key elements 5 and 6, which focus on the balance of plant design. The SMART reactor is ranked in the fourth place, only 0.01 points behind SMR-160. This reactor design received only one lowest grade, caused by its lowest net thermal efficiency. In other key elements, SMART received a moderate rating. Overall, compared to SMR-160, the SMART reactor proved to be a reliable SMR design without any significant flaws. The lowest overall rating was received by HTR-PM, despite receiving the highest grading in some key elements. For example, HTR-PM obtained the most points in KE 5, mainly thanks to its highest net thermal efficiency. HTR-PM also scored the most points in KE 8 because it is the only technology among the SMR designs in this RTA that is already in operation. On the other hand, HTR-PM ranked the lowest in 5 out of 10 key elements, specifically in key elements 1, 2, 3, 6, and 10. Several of these low scores were primarily attributed to the use of TRISO fuel instead of conventional nuclear fuel in other SMRs. The RTA tool results show that, as the Czech Republic navigates its energy transition, SMRs can play a significant role in achieving a balanced and sustainable energy future. With their potential to provide clean and reliable electricity, foster economic growth, and contribute to global efforts in mitigating climate change, SMRs represent a viable option for the country's energy diversification and decarbonization goals.

3.2. Egypt. The reactor technology assessment (RTA) for Egypt revealed that the RITM-200 reactor emerged as the most suitable technology for the country's nuclear plan, aligning well with their policy and regulations. NuScale secured the second position, and the BWRX-300 ranked third. The SMART reactor followed in the fourth position, while the HTR-PM obtained the last spot in the evaluation as illustrated in Figures 8 and 9 and Table 3. The evaluation process considered various key elements (KE), resulting in diverse scores for each SMR technology. The RITM-200 reactor scored the highest in KE 1 due to its comprehensive coverage of subtopics, including environmental and radiological impact. Notably, RITM-200 prioritizes preventing abnormal operation and accidents, drawing from the experience gained in marine plants and nuclear generating stations. In addition, the design adheres to Russian laws, standards, and regulations for nuclear power plants and aligns with safety principles established by the International Atomic Energy Agency (IAEA). For KE 2, both NuScale and RITM performed equally well, meeting the requirements of the rationale. On the other hand, HTR-PM received a lower score due to the unavailability of a reprocessing plan for long-term spent fuel. However, all five SMR technologies scored similarly in terms of nuclear safety (KE 3), as they all fulfilled the necessary safety features, including the implementation of the defence-in-depth philosophy, protection



	KE1	KE2	KE3	KE4	KE5	KE6	KE7	KE8	KE9	KE10
R#1	0.27	0.43	0.65	0.39	0.2	0.3	0.24	0.49	0.41	0.4
R#2	0.29	0.38	0.6	0.39	0.17	0.28	0.19	0.48	0.41	0.32
R#3	0.25	0.23	0.57	0.41	0.27	0.2	0.23	0.55	0.37	0.29
R#4	0.34	0.38	0.64	0.43	0.25	0.3	0.17	0.51	0.36	0.42
R#5	0.36	0.42	0.63	0.31	0.2	0.25	0.17	0.44	0.37	0.37

Figure 6: RTA results for the Czech Republic.

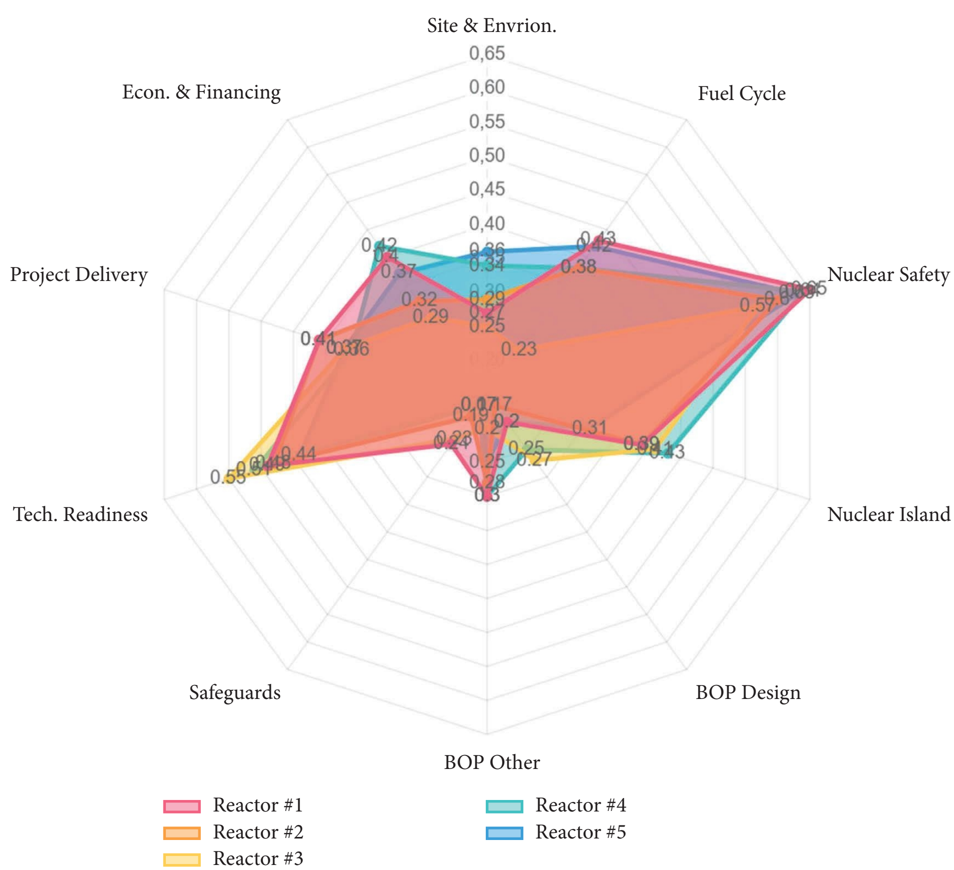


Figure 7: Final results of RTA for the Czech Republic for all key elements.

against internal and external hazards, and mitigation of severe accidents. In evaluating KE 4, the BWRX-300 excelled by providing sufficient data information and meeting all requirements. Some factors affecting their score were a high-capacity factor of 95% and the ability to achieve constructability as first-of-a-kind (FOAK) within 24 months. In contrast, RITM scored lower with a capacity factor of 90% and a longer FOAK construction time of 6 years. For KE 5,

Table 2: Final scoring of 5 SMRs for the Czech Republic.

Reactor type	RTA results
R#1 (NuScale)	3.78
R#2 (SMART)	3.51
R#3 (HTR-PM)	3.37
R#4 (BWRX-300)	3.80
R#5 (SMR-160)	3.52

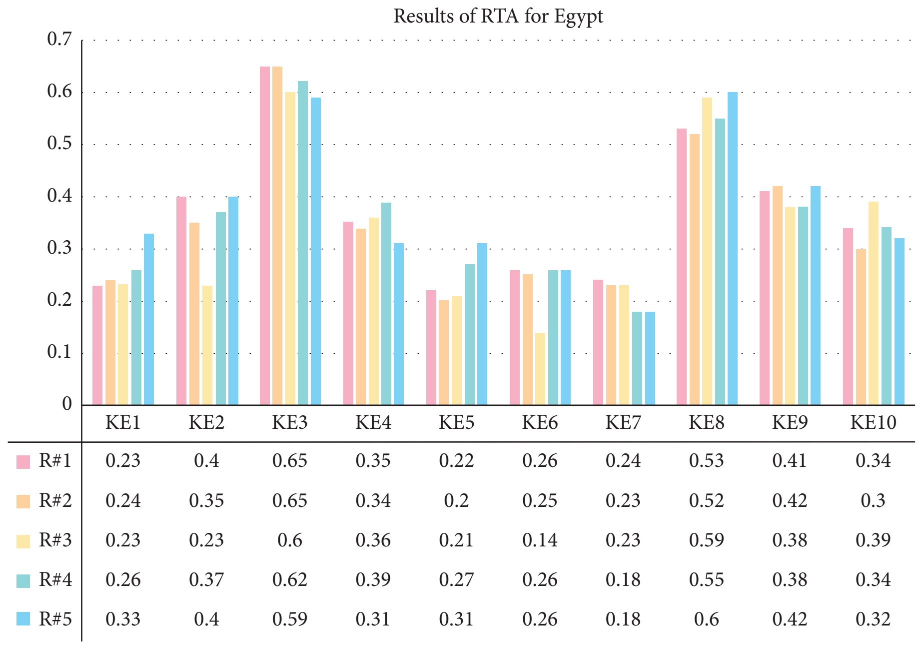


Figure 8: RTA results for Egypt.

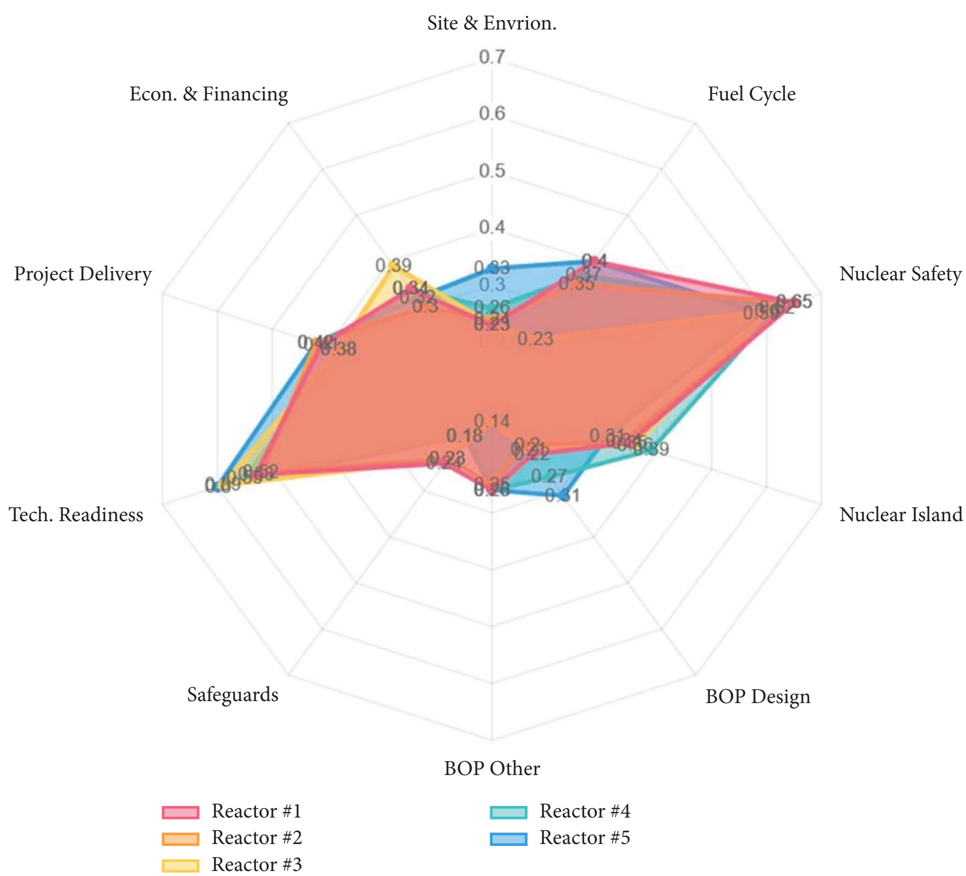
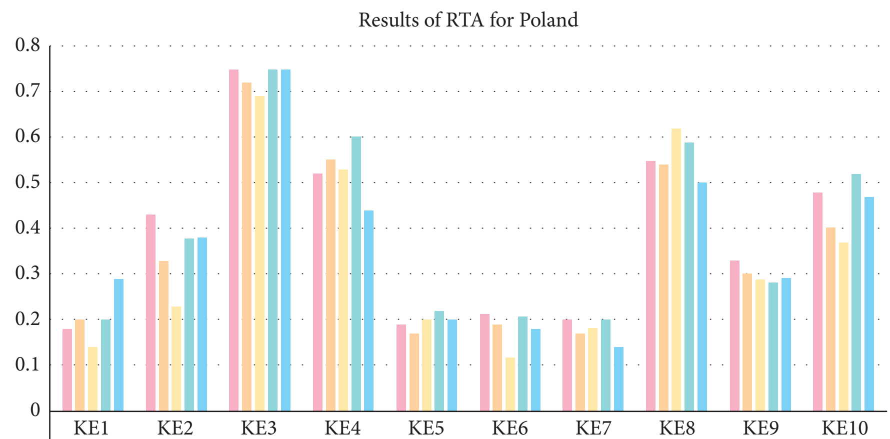


Figure 9: Final results of RTA for Egypt for all key elements.

Table 3: Final scoring of 5 SMRs for the Egypt.

Reactor type	RTA results
R#1 (NuScale)	3.63
R#2 (SMART)	3.50
R#3 (HTR-PM)	3.36
R#4 (BWRX-300)	3.62
R#5* (RITM-200)	3.72

Note: *reference to that is only for Egypt.



	KE1	KE2	KE3	KE4	KE5	KE6	KE7	KE8	KE9	KE10
R#1	0.18	0.43	0.75	0.52	0.19	0.21	0.2	0.55	0.33	0.48
R#2	0.2	0.33	0.72	0.55	0.17	0.19	0.17	0.54	0.3	0.4
R#3	0.14	0.23	0.69	0.53	0.2	0.12	0.18	0.62	0.29	0.37
R#4	0.2	0.38	0.75	0.6	0.22	0.21	0.2	0.59	0.28	0.52
R#5	0.29	0.38	0.75	0.44	0.2	0.18	0.14	0.5	0.29	0.47

Figure 10: RTA results for Poland.

which assesses the balance of plant (BOP) design and grid integration, the SMART reactor received the lowest score primarily due to its lower net thermal efficiency of 29.3%. Similarly, HTR-PM scored the lowest in KE 6, partly due to a lack of information and its exclusive focus on electricity production. In KE 7 and KE 8, safeguards and technology readiness, respectively, BWRX and RITM had limited data, resulting in their lowest scores for safeguards, but they scored higher in technology readiness due to their construction as real modules. Conversely, SMART and RITM performed well in KE 9 due to the clear information available about supplier holder issues and spent fuel management services. In the economics topic (KE 10), cost information was not available for all SMRs. However, China announced the cost of $2 billion per reactor for the HTR-PM, which is lower than the estimated values for the other reactors. This cost factor contributed to HTR-PM achieving the highest score in that particular topic. In summary, the RTA provided valuable insights into the strengths and weaknesses of each SMR technology, leading to the selection of RITM-200 as the most suitable option for Egypt's nuclear plan, with NuScale and BWRX-300 closely following. The evaluation considered multiple key elements, and the scores varied based on each technology's performance in fulfilling the respective criteria.

3.3. Poland. According to the RTA performed for Poland, the results show that BWRX-300 is the most suitable technology as it meets the Polish needs and energy policy at the highest level. In the second place was NuScale, and in the third place was SMR-160. The SMART and HTR-PM designs occupied the last two positions. In KE 3 nuclear safety, all SMRs met high standards equally, as they all met the nuclear safety standards very well. In KE 5 balance of plant and grid integration, results were comparable. Figures 10 and 11 and Table 4 display the final results of the RTA analysis for Poland. The evaluations of the BWRX-300 and NuScale designs aligned closely for all ten key elements in relation to Poland. Nevertheless, NuScale was positioned second in the final assessment, as the BWRX-300 garnered comparable or slightly elevated scores. When it comes to the NuScale SMR, in KE 2, fuel cycle, its design outperformed the other analyzed designs, securing the highest score. One of the contributions was the results of topic KT 2.6 that addressed fuel versatility. NuScale's UO2 pellet design, 17×17 square, enrichment ≤4.95%, accommodates recycled and MOX fuel, proven through studies, enhancing NuScale SMR adaptability. In KE 9, the NuScale design received the highest score. The most contribution to it had the topic KT 9.1 and that the results of the probabilistic risk assessment (PRA)

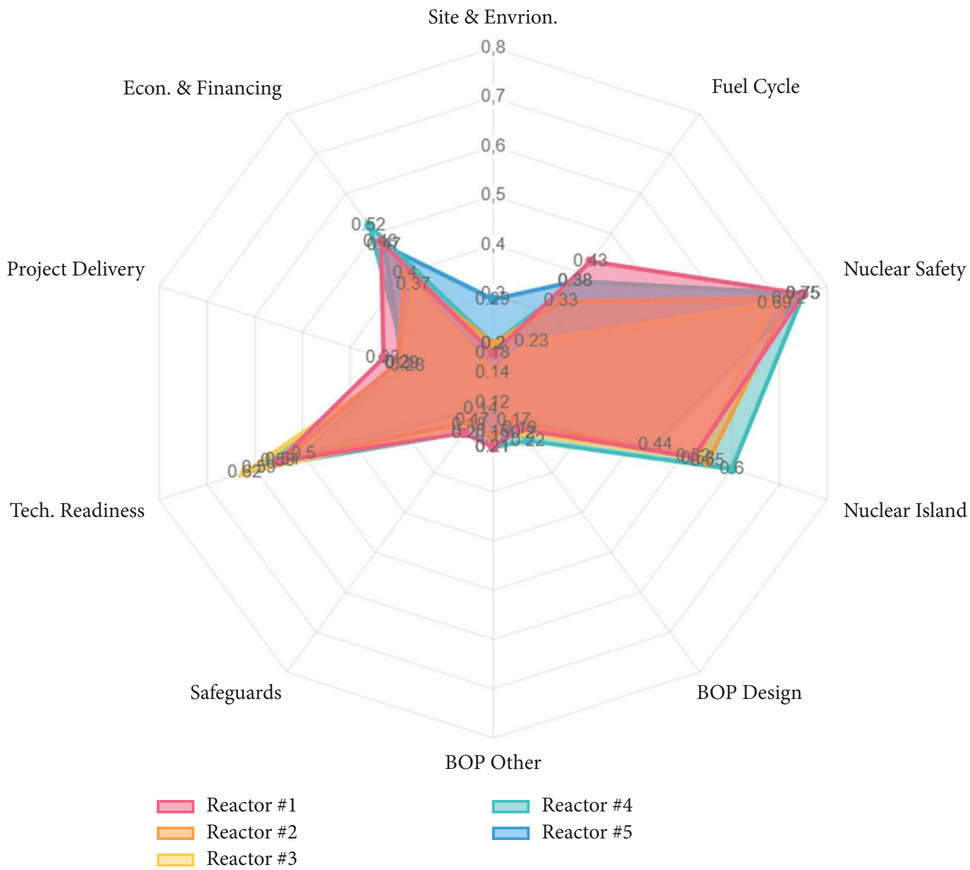


Figure 11: Final results of RTA for Poland for all key elements.

Table 4: Final scoring of 5 SMRs for Poland.

Reactor type	RTA results
R#1 (NuScale)	3.84
R#2 (SMART)	3.57
R#3 (HTR-PM)	3.37
R#4 (BWRX-300)	3.95
R#5 (SMR-160)	3.64

reports are periodically published for this design. The SMR-160's placement in the third position primarily stemmed from its irregular performance. It got the highest total score in KE 1 site and environment particularly due to its crucial contribution, topic KT 1.8, addressing Poland's needs for external event protection. With walk-away safety and an underground design, SMR-160 withstands cyclones, tsunamis, floods, earthquakes, fires, and aircraft impact, prioritizing public safety. However, in KE 7, SMR-160 scored the lowest due to lacking information about cyber security protection, emphasized in KT 7.4 given Poland's concern after Russian cyber attacks on Zaporizhzhia Nuclear Power Plant [56]. The least advancement in constructing the first unit resulted in SMR-160 garnering its lowest score in KE 4 nuclear island among the designs under examination. The fourth position was secured by the SMART reactor. This particular design acquired the lowest score only in KE 5 primarily due to its smallest percentage of the net thermal efficiency when compared to other designs. In terms of overall design competence, the SMART reactor and SMR-160 displayed similar levels of performance. The HTR-PM garnered the lowest overall evaluation. This design received the highest score in KE 8 as the only technology among the SMR designs in this RTA that is already operational. Conversely, HTR-PM ranked at the bottom in five out of the ten key elements, i.e., KEs 1, 2, 3, 6, and 10. Many of these lower scores were predominantly attributed to the utilization of TRISO fuel, distinct from the conventional nuclear fuel used in other SMRs, resulting in heightened costs and limited fuel supplier options as TRISO fuel was not easily available. The utilization of uranium oxide fuel is favored due to its well-known production costs, whereas estimates for the expenses associated with alternative fuel types such as TRISO fuels carry significant levels of uncertainty [57].

4. Conclusion

The nuclear reactor technology assessment (RTA) is a crucial process that assists countries in achieving their goals in nuclear power programs. The International Atomic Energy Agency (IAEA) provides a methodology for RTA to evaluate and select the most suitable reactor technology for specific program objectives. The assessment encompasses safety, performance, economics, and environmental impact criteria. During the RTA, thorough examination of reactor technologies takes place to determine their suitability for specific applications and project needs. Design characteristics, technical features, safety systems, operational performance, and fuel types are considered. Safety assessment includes evaluating safety features, risk assessment, emergency response capabilities, and potential impacts on public and environmental safety. Performance analysis involves assessing power output, efficiency, operational flexibility, load-following capability, and operational lifetime. Economic evaluation is essential, considering capital costs, construction timelines, operation and maintenance expenses, fuel costs, and potential revenue. Environmental impact examines aspects such as greenhouse gas emissions, waste management, water usage, land footprint, and effects on biodiversity. Regulatory compliance and adherence to safety and security guidelines are crucial factors in the assessment. The methodology aids stakeholders in making informed decisions by evaluating the benefits and challenges of different reactor technologies in alignment with project goals, safety requirements, energy needs, and economics. In this study, the RTA is applied to the Czech Republic, Egypt, and Poland to choose between different SMR designs. For all countries, the analysed designs were as follows: NuScale, SMART, HTR-PM, and BWRX-300. For the Czech Republic and Poland, the fifth design considered in RTA was SMR-160. For Egypt, the fifth analysed technology was RITM-200. The choice of the most suitable reactor technology varies depending on each country's specific policies, regulations, and energy needs. For the Czech Republic and Poland, the BWRX-300 is deemed the most suitable reactor technology, while for Egypt, the RITM-200 aligns with their SMR nuclear technology plan. Ultimately, RTA contributes to the advancement of nuclear power generation by identifying promising reactor technologies for future deployment. This helps address global energy challenges and work towards a sustainable and secure energy future.

Data Availability

The data employed in this study to underpin our findings can be obtained from the authors upon request by emails waadsaleh78@gmail.com, dalibor.kojecky37@email.cz, e.macieja@student.uw.edu.pl, jykim@kings.ac.kr.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

This research was supported by the 2023 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), the Republic of Korea.

References

[1] World Nuclear Association, "Emerging nuclear energy countries," 2023, https://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx.

[2] L. Liu, H. Guo, L. Dai et al., "The role of nuclear energy in the carbon neutrality goal," *Progress in Nuclear Energy*, vol. 162, Article ID 104772, 2023.

[3] R. J. Budnitz, H. H. Rogner, and A. Shihab-Eldin, "Expansion of nuclear power technology to new countries–SMRs, safety culture issues, and the need for an improved international safety regime," *Energy Policy*, vol. 119, pp. 535–544, 2018.

[4] International Atomic Energy Agency, *Nuclear Reactor Technology Assessment for Near Term Deployment*, International Atomic Energy Agency, Vienna, Austria, 2022.

[5] International Atomic Energy Agency, *Nuclear Reactor Technology Assessment for Near Term Deployment*, International Atomic Energy Agency, Vienna, Austria, 2013.

[6] International Atomic Energy Agency, *Evaluation of the Status of National Nuclear Infrastructure Development*, International Atomic Energy Agency, Vienna, Austria, 2016.

[7] International Atomic Energy Agency, *Milestones in the Development of a National Infrastructure for Nuclear Power*, International Atomic Energy Agency, Vienna, Austria, 2015.

[8] International Atomic Energy Agency, *Invitation and Evaluation of Bids for Nuclear Power Plants*, International Atomic Energy Agency, Vienna, Austria, 2011.

[9] International Atomic Energy Agency, "Nuclear technology review," 2022, https://www.iaea.org/sites/default/files/gc/gc66-inf4.pdf.

[10] G. Locatelli, C. Bingham, and M. Mancini, "Small modular reactors: a comprehensive overview of their economics and strategic aspects," *Progress in Nuclear Energy*, vol. 73, pp. 75–85, 2014.

[11] M. Z. Zolkaffly and K.-I. Han, "Reactor technology assessment and selection utilizing systems engineering approach," *AIP Conference Proceedings*, vol. 1584, no. 1, pp. 22–31, 2014.

[12] S. Short and B. Schmitt, "Deployability of small modular nuclear reactors for alberta applications—phase II," Technical Report, Alberta Innovates, Calgary, Canada, 2018.

[13] M. R. Weimar, A. Zbib, D. Todd, J. Buongiorno, and K. Shirvan, "Techno-economic assessment for generation III+ small modular reactor deployments in the Pacific Northwest," PNNL-30225, Packific Northwest National Laboratory, Richland, WA, USA, 2021.

[14] T. Murakami and V. Anbumozhi, *Small Modular Reactor (SMR) Deployment: Advantages and Opportunities for ASEAN*, Economic Research Institute for ASEAN and East Asia, Jakarta, Indonesia, 2022.

[15] S. U.-D. Khan, S. U. D. Khan, S. Haider et al., "Development and techno-economic analysis of small modular nuclear reactor and desalination system across Middle East and North Africa region," *Desalination*, vol. 406, pp. 51–59, 2017.

[16] International Atomic Energy Agency, *Assessment of Small Modular Reactors Using IAEA Reactor Technology Toolkit: Issues and Challenges (Ghana)*, International Atomic Energy Agency, Vienna, Austria, 2019.

[17] World Nuclear Association, "Space allocated at Temelín for future SMRs," 2022, https://www.world-nuclear-news.org/Articles/Space-allocated-at-Temelin-for-future-SMR.

[18] A. Abuzeid, "Egypt is studying the construction of small modular reactors," 2020, https://nbn.business/egypt-is-studying-the-construction-of-small-modular-reactors/.

[19] World Nuclear Association, "Polish plans for large and small reactors progress," 2023, https://world-nuclear-news.org/Articles/Polish-plans-for-large-and-small-reactors-progress.

[20] R. W. Barron and M. C. Hill, "A wedge or a weight? Critically examining nuclear power's viability as a low carbon energy

source from an intergenerational perspective," *Energy Research & Social Science*, vol. 50, pp. 7–17, 2019.
[21] International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments: A Supplement to the IAEA Advanced Reactors Information System (ARIS)*, International Atomic Energy Agency, Vienna, Austria, 2020.
[22] A. Tokuhiro, F. Genco, and M. Gomez-Fernandez, "Technical and non-technical issues and challenges to realize nuclear power and SMR safety-in-design to levelized the perception of SMRs as part of lower carbon national energy portfolio," in *Proceedings of the G4SR-Generation IV and SMR Conference*, pp. 3–6, Toronto, Canada, December 2022.
[23] M. Ramana and Z. Mian, "One size doesn't fit all: social priorities and technical conflicts for small modular reactors," *Energy Research & Social Science*, vol. 2, pp. 115–124, 2014.
[24] H. Hidayatullah, S. Susyadi, and M. H. Subki, "Design and technology development for small modular reactors–Safety expectations, prospects and impediments of their deployment," *Progress in Nuclear Energy*, vol. 79, pp. 127–135, 2015.
[25] S. Barenghi, S. Boarin, and M. E. Ricotti, "Investment in different sized SMRs: economic evaluation of stochastic scenarios by INCAS code," in *Proceedings of the 2012 International Congress on Advances in National Power Plants (ICAPP'12)*, pp. 2783–2792, Chicago, IL, USA, June 2012.
[26] I. Playbell, "Economy, safety and applicability of small modular reactors," *Proceedings of the Institution of Civil Engineers-Energy*, vol. 170, no. 2, pp. 67–79, 2017.
[27] World Nuclear Association, "Facilitating international licensing of small modular reactors," *Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group of the World Nuclear Association*, World Nuclear Association, London, UK, 2015.
[28] E. Shobeiri, F. Genco, D. Hoornweg, and A. Tokuhiro, "Small modular reactor deployment and obstacles to Be overcome," *Energies*, vol. 16, no. 8, p. 3468, 2023.
[29] International Atomic Energy Agency, "Small Modular Reactors: a new nuclear energy paradigm," 2022, https://nucleus.iaea.org/sites/smr/Shared20Documents/SMR20Booklet_22-9-22.pdf.
[30] International Energy Agency, "Czech Republic country profile," 2022, https://www.iea.org/countries/czech-republic.
[31] Ministry of Industry and Trade Prague, *The National Energy and Climate Plan of the Czech Republic*, Ministry of Industry and Trade Prague, Prague, Czech Republic, 2019.
[32] International Atomic Energy Agency, "Country nuclear power profiles, Czech REPUBLIC," 2022, https://cnpp.iaea.org/countryprofiles/CzechRepublic/CzechRepublic.htm.
[33] F. Černoch and T. Vlček, *The Energy Sector and Energy Policy of the Czech Republic*, Masaryk University, Brno, Czechia, 2013.
[34] United Nations Framework Convention on Climate Change, "Egypt'S first updated nationally determined contributions," 2022, https://unfccc.int/sites/default/files/NDC/2022-07/Egypt20Updated20NDC.pdf.
[35] D. Cauich-López, L. F. B. Payan, A. M. N. Abdelhalim et al., "Egypt and nuclear energy: aspects, reasons and future," *IOP Conference Series: Earth and Environmental Science*, vol. 337, no. 1, Article ID 012081, 2019.
[36] Europarl, "Egypt's climate change policies State of play ahead of COP27," 2022, https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/738187/EPRS_BRI%282022%29738187_EN.pdf.
[37] Ministry of Electricity and Renewable Energy, "Renewable Energy Targets," 2021, http://nrea.gov.eg/test/en/About/Strategy.
[38] Twin Association, "Nuclear power in Egypt," 2023, https://world-nuclear.org/information-library/country-profiles/countries-a-f/egypt.aspx.
[39] International Energy Agency, "Poland country profile," 2022, https://www.iea.org/countries/poland.
[40] Council of the European Union, "Energy and climate—elements of the final compromise Brussels," 2008, https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/104672.pdf.
[41] European Commission, "Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions, stepping up europe's 2030 climate ambition," 2021, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562.
[42] M. K. I. Środowiska, "National energy and climate plan for the years 2021-2030," 2021, https://www.gov.pl/web/klimat/national-energy-and-climate-plan-for-the-years-2021-2030.
[43] Ministry of Climate and Environment Republic of Poland, "Energy policy of Poland until 2040 (EPP2040)," 2021, https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040.
[44] Ministry of Climate Polish Nuclear Power Programme, "Journal of laws of the republic of poland," 2020, https://www.gov.pl/web/paa-en/Polish-Nuclear-Power-Program.
[45] National Centre for Nuclear Research, "Concept design of the HTGR-POLA research reactor," 2021, https://www.ncbj.gov.pl/en/aktualnosci/concept-design-htgr-pola-research-reactor.
[46] Notes From Poland, "Poland aims to produce three quarters of power from renewables and nuclear by 2040," 2023, https://notesfrompoland.com/2023/04/04/poland-aims-to-produce-three-quarters-of-power-from-renewables-and-nuclear-by-2040/#:~:text=website%20uses%20cookies.-,Poland%20aims%20to%20produce%20three%20quarters%20of,renewables%20and%20nuclear%20by%202040&text=Poland's%20climate%20ministry%20has%20outlined,and%20almost%2023%25%20from%20nuclear.
[47] "Uchwała Nr 215/2022 Rady Ministrów Z Dnia 2 Listopada 2022 R. W Sprawie Budowy Wielkoskalowych Elektrowni Jądrowych W Rzeczypospolitej Polskiej. {Resolution of the Council of Ministers on the Construction of Large-Scale Nuclear Power Plants in the Republic of Poland.}," 2022, https://isap.sejm.gov.pl/isap.nsf/download.xsp/WMP20220001124/O/M20221124.pdf.
[48] World Nuclear news, "Joint venture established for second Polish plant," 2023, https://www.world-nuclear-news.org/Articles/Joint-venture-established-for-second-Polish-plant.
[49] World Nuclear news, "BWRX-300 meets Polish safety requirements, says regulator," 2023, https://www.world-nuclear-news.org/Articles/BWRX-300-meets-Polish-safety-requirements,-says-re.
[50] World Nuclear news, "Decision-in-principle for Polish SMR power plant," 2023, https://www.world-nuclear-news.org/Articles/Decision-in-principle-for-Polish-SMR-power-plant.
[51] K. Demjancukova and L. Pecinka, *Seismic hazard Assessment for NPPs in Czech Republic*, International Atomic Energy Agency, Vienna, Austria, 2014.
[52] K. El-Adham and S. El-Hemamy, "Modelling of seismic hazard for the El-Dabaa area, Egypt," *Bulletin of Engineering Geology and the Environment*, vol. 65, no. 3, pp. 273–279, 2006.
[53] D. Barkhatov, P. Marek, J. M. Rolenc, and J. Antal, "Nuclear power expansion and its economic implications to the energy security of the Czech Republic," *Současná Evropa*, vol. 2019, no. 1, pp. 29–51, 2019.

[54] A. A. Kareem Gerges, *Egypt's nuclear power program: security and economic risks*, Ph.D. thesis, American University of Beirut, Beirut, Lebanon, 2018.
[55] J. Gierszewski, Ł. Młynarkiewicz, T. R. Nowacki, and J. Dworzecki, "Nuclear power in Poland's energy transition," *Energies*, vol. 14, no. 12, p. 3626, 2021.
[56] D. E. Sanger, "The operator of Ukraine's nuclear plants says it faced an ambitious cyberattack," 2022, https://www.nytimes.com/2022/08/16/world/europe/the-operator-of-ukraines-nuclear-plants-says-it-faced-an-ambitious-cyberattack.html.
[57] L. Carlson, Z. Wu, J. Olson, and L. Liu, "An economic cost assessment on HALEU fuels for small modular reactors," *Science and Technology of Nuclear Installations*, vol. 2020, Article ID 8815715, 6 pages, 2020.