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SMALL MODULAR REACTOR TECHNOLOGY ASSESSMENT IN THE PHILIPPINES TOWARDS DECARBONIZATION

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This Special Problem of **PAULINE BIANCA R. ALFONSO** titled: **"SMALL MODULAR REACTOR TECHNOLOGY ASSESSMENT IN THE PHILIPPINES TOWARDS DECARBONIZATION"** is hereby accepted by the Faculty of Management and Development Studies, U.P. Open University, in partial fulfillment of the requirements for the Master of Environment and Natural Resources Management.

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DECLARATION

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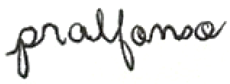
I. The special problem comprises only my original work towards the

MENRM except where indicated in the Preface

II. Due acknowledgment has been made in the text to all other material used

III. The special problem is fewer than 25,000 words in length, exclusive of tables, maps, bibliographies and appendices.



Pauline Bianca R. Alfonso

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TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

This study evaluates the integration of Small Modular Reactor (SMR) technologies into the Philippines' energy framework to address rising energy demand, reduce greenhouse gas emissions, and achieve a sustainable low-carbon future. Utilizing the International Atomic Energy Agency's Reactor Technology Assessment (IAEA's RTA) methodology, five SMR technologies—BWRX-300, HTR-PM, NuScale, RITM-200N, and SMART—were assessed against ten key elements (KEs).

The evaluation employed the Simple Multi-Attribute Rating Technique (SMART) to assign weights and scores to each KE based on national policy priorities. High-priority national objectives include ensuring nuclear safety, transitioning to low-carbon energy systems, promoting stable and affordable power, and establishing robust legal and regulatory frameworks. The BWRX-300 emerges as the most suitable option, scoring highest in site adaptability, safety, seismic resilience, and compatibility with the Philippines' diverse geographic and grid conditions. Its modular design and passive safety systems make it particularly well-suited for deployment in the country's seismically active and archipelagic environment. Monte Carlo simulations highlighted the sensitivity of the RTA scoring process to variations in environmental parameters, underscoring the importance of accurate assessments. These findings offer a robust framework for informed decision-making, positioning nuclear energy as a key component in the Philippines' sustainable energy strategy.

Keywords: Small Modular Reactors; Reactor Technology Assessment; Nuclear Energy; Sustainable Development; Philippines

I. INTRODUCTION

The global shift toward clean energy production, as outlined in the Paris Agreement, has been adopted by over 180 countries under the United Nations Framework Convention on Climate Change (UNFCCC). As a signatory to this accord, the Philippines is actively aligning its energy framework with this global transition. The Philippine government is prioritizing a move to cleaner, more sustainable, and resilient energy systems to meet its commitment.

In 2022, the country's power generation was predominantly reliant on coal, which accounted for 59.6% of total power production (Balita, 2024). Renewable energy followed at 22%, while natural gas and oil-based sources contributed 16% and 2.3%, respectively. This heavy dependence on coal has significant environmental repercussions, with the energy sector responsible for 56.2% of the nation’s greenhouse gas (GHG) emissions—equivalent to 135.7 million tons of CO_2 ($MtCO_2e$). Recognizing the urgency of a low-carbon transition, the Department of Energy (DOE) is exploring nuclear energy as a viable solution.

As part of its commitment to international nuclear collaboration, the Philippines participated in the 68th General Conference of the International Atomic Energy Agency (IAEA) in Vienna, Austria, from September 16–20, 2024 (Philippine Nuclear Research Institute, 2024). During the event, DOE Undersecretary Sharon Garin introduced a new energy roadmap aimed at achieving operational nuclear power plants by 2032, starting with an initial capacity of 1,200 megawatts and scaling to 4,800 megawatts by 2050. This initiative seeks to address the country’s rapidly increasing energy demand, projected to quadruple between 2020 and 2040, with an annual growth rate of 7%. To meet this demand, the Philippines must increase its installed capacity from 22,317 MW in 2019 to 114,601 MW by 2040.

Globally, nuclear energy is the second-largest low-carbon energy source after hydropower (Jawerth, 2020). Compared to other electricity sources, it boasts the lowest carbon footprint, requires fewer materials, and occupies significantly less land. Moreover, nuclear energy is considered the second safest energy source globally. Although spent fuel is highly radioactive and generates heat, it can be safely managed through storage in cooling pools, dry storage systems, or recycling (Grossi, 2024). Recognizing these advantages, environmental activists have signed a declaration during COP28 in Dubai to triple global nuclear energy capacity by 2050, aiming to meet climate goals and growing energy demands (Laffan, 2024).

Currently, nuclear power provides about 9% of the world's electricity from approximately 440 reactors (World Nuclear Association, 2024). Innovations in nuclear technology have led to the development of Small Modular Reactors (SMRs), compact designs with capacities of 300 MWe or less. SMRs, which are factory-fabricated, offer shorter construction times, scalability, and cost-effectiveness (World Nuclear Association, 2024a). With inherent and passive safety features, SMRs are a promising option for countries seeking to diversify their energy mix.

The integration of nuclear energy into the Philippines' energy mix presents a strategic opportunity to establish a sustainable and secure energy landscape. The suitability of SMR technologies such as BWRX-300, HTR-PM, NuScale, RITM-200N, and SMART will be evaluated using the IAEA's Reactor Technology Assessment (RTA) methodology. These technologies, whether operational, under construction, or approved by regulators, will be evaluated for their applicability in the Philippine context. This evaluation aligns with key national strategies:

1. AmBisyon Natin 2040: The long-term vision for a prosperous Filipino society.

2. 8-Point Socio-Economic Agenda: Focused on economic transformation, job creation, and affordable energy as outlined in the Philippine Development Plan (PDP) 2023–2028.
3. United Nations Sustainable Development Goals (SDGs): Ensuring clean, reliable, and sustainable energy access for all.

This study aims to evaluate nuclear technologies based on national priorities and conditions using the IAEA's RTA methodology. As an IAEA Member State since 1958, the Philippines has benefitted from the agency's extensive support in nuclear development. The DOE recognizes the RTA methodology as an essential framework for selecting nuclear power plant technologies that align with national needs (International Atomic Energy Agency, 2022). This structured methodology evaluates reactor designs based on safety, economic viability, scalability, and compatibility with local conditions. Through informed decision-making, deploying nuclear power projects will strengthen the Philippines' energy infrastructure, ensuring affordability, reliability, and sustainability while addressing the challenges of climate change.

II. REVIEW OF LITERATURE

Climate change is a global issue that provokes many countries to commit to a low-carbon transition concerning energy production. The Philippines is located in the Pacific Typhoon Belt and the Pacific Ring of Fire, which means it often experiences natural disasters. The Institute for Economics and Peace (2019) reported that the Philippines is the country most at risk from the effects of climate change. Thus, the government signed the Paris Agreement on Climate Change to commit to a 75% reduction and avoidance of GHG emissions by 2030. More than half of GHG emissions in the country come from the energy sector. Hence, the Department of Energy (DOE) crafted the overall government energy agenda that aims to facilitate access to affordable energy, secure a reliable and resilient energy supply, and transition to clean, sustainable, and climate-centered energy resources, coined as the ARC objectives.

Macmac et al. (2023) highlighted nuclear energy as the most viable option for meeting the Philippines' growing energy demand while supporting its commitment to reducing greenhouse gas emissions. Their findings align with Sadekin et al. (2019), who identified nuclear power as the most beneficial clean energy option. Beyond addressing environmental concerns, nuclear energy offers the dual advantage of meeting increasing electricity demand and presenting significant opportunities for the country. Nuclear energy offers opportunities for employment, energy security, and environmental sustainability. Public support for reviving the Bataan Nuclear Power Plant and building new facilities has grown due to effective awareness campaigns promoting nuclear power as part of the energy mix. However, the future of nuclear energy in the Philippines is highly dependent on its high potential for energy generation, increased readiness of its technical capacity, and promising sustainable impacts.

Fossil fuels will go extinct by the year 2050 or 2100 at the current rate of consumption, so building nuclear power plants is a wise strategic move toward the development of clean energy. Nuclear energy is not carbon neutral, but it does emit far less carbon dioxide than fossil fuels do, with nuclear electricity chains emitting comparatively less greenhouse gas than other energy structures (Sadekin et al., 2019).

Rehm (2022) claimed that advanced nuclear technology is one of the best ways to reach carbon neutrality. It is safe, produces less waste, can last for thousands of years, provides heat for factories, and can help reduce the use of fossil fuels in making chemicals. A case study for Ontario is conducted by Rosen & Dincer (2007) using the nuclear and fossil facilities of the major provincial electrical utilities. It is noted that the province and its electrical utilities can benefit economically from the implementation of utility-based co-generation, and that nuclear energy can be used in place of fossil fuels.

According to Crismundo (2024), DOE Secretary Raphael Lotilla confirmed plans to build eight 150-MW small modular reactors (SMRs) by 2032, aiming to add 1,200 MW of nuclear power. Based on the DOE’s clean energy plan, another 1,200 MW is expected by 2035 and 2,400 MW more by 2050. About 12 sites in western parts of the country are being considered for future nuclear plants.

During the Asia-Pacific Economic Cooperation (APEC) Summit in San Francisco on November 16, 2023, the United States and the Philippines signed the "123 Agreement" on civil nuclear cooperation. This will allow U.S. companies to export SMRs to the Philippines. With access to U.S. materials and equipment, the U.S. and the Philippines can work together to use new technologies like SMRs to help meet climate goals and strengthen the Philippines' energy security and power supply. The agreement also includes rules both countries must follow, such as safety checks by the IAEA, protecting nuclear materials, and limits on activities like enriching or sharing certain items without each other's approval (Yurman, 2023).

In 2017, the Department of Energy (DOE) began looking into the use of small nuclear reactors in the Philippines, starting with a possible project in Sulu province, Mindanao. This was part of a nuclear cooperation agreement with Rosatom Overseas. In 2019, the DOE and Rosatom signed another deal to study the use of RITM-200 reactors for a small nuclear power plant. In 2018, the DOE also announced that Korea Hydro & Nuclear Power (KHNP) would study the possible construction of a 100 MWe SMART small modular reactor (SMR) in the Cagayan Economic Zone Authority (CEZA) in Sta. Ana, Cagayan (World Nuclear Association, 2024b).

NuScale Power, a U.S.-based company, has also shown interest in building SMRs in the Philippines. On May 1, 2023, NuScale met with the Philippine government and Prime Infrastructure Capital Inc. (Prime Infra) in Washington, D.C. NuScale's SMR, called the NuScale Power Module, is a pressurized water reactor (PWR) that produces 77 MWe and was approved by the U.S. Nuclear Regulatory Commission in 2020. These modules are offered in different sizes, such as the VOYGR-12 with 12 units producing up to 924 MWe. Smaller versions with four or six units are also available.

In another development, Meralco, a major power distributor in the Philippines, partnered with U.S.-based Ultra Safe Nuclear Corporation (USNC) to explore micro-modular reactors (MMRs). This agreement was signed during President Ferdinand Marcos Jr.'s visit to the U.S. for the Asia-Pacific Economic Cooperation summit.

USNC will conduct a four-month pre-feasibility study to help Meralco understand how MMR can be used in the Philippines. Depending on the results, Meralco may proceed with a full feasibility study to consider the future use of MMR systems.

Saleh et al. (2023) examined the IAEA's RTA toolkit for deploying SMRs in Egypt, Poland, and the Czech Republic. The study highlights SMRs' potential to boost energy security, cut greenhouse gas emissions, and promote sustainability. Key SMR technologies such as NuScale, SMART, HTR-PM, BWRX-300, SMR-160, and RITM-200 are evaluated. For the Czech Republic, the BWRX-300 was preferred due to its suitability for district heating and energy diversification as the country shifts towards nuclear power, which made up 36% of its electricity generation in 2021. In Egypt, the RITM-200 was deemed most suitable, owing to its compatibility with the country's nuclear energy strategy. Egypt, with a rapidly growing population, is addressing rising energy demands by reviving its nuclear ambitions. Egypt has begun constructing its first nuclear power plant with plans to add more units and explore SMRs for cost-efficient and flexible energy solutions. Poland also favored the BWRX-300, given its alignment with the nation's transition from coal to nuclear energy. Poland's energy sector is undergoing a transformation driven by European Union climate targets and declining coal production. With plans to diversify its energy mix, Poland aims to introduce nuclear power as part of its National Energy Policy 2040, targeting 23% nuclear electricity generation by 2040 through large reactors and SMRs.

The RTA methodology was created by the IAEA to set standards and guidelines for the objective application of the RTA process when launching or expanding a nuclear power program. Three progressive phases and 19 infrastructure issues are identified by the IAEA's Milestones approach. The RTA is based on several technical aspects of nuclear technology, which are organized into key elements (KEs) and key topics (KTs). This process helps Member States measure and evaluate these elements and topics during feasibility studies. It guides them in choosing the reactor technology that best fits their national needs, goals, and requirements (International Atomic Energy Agency, 2022).

III. STATEMENT OF THE STUDY

The Philippines relies on imports to nearly half of its energy, posing challenges for energy security and economic stability. The heavy use of coal for power generation exacerbates these issues. At the current consumption rate, coal-dependent countries like the Philippines may face significant difficulties as global coal usage declines between 2050 and 2100. Coal power plants not only contribute to high electricity costs but are also major sources of GHG emissions.

In addition, energy demand is rapidly rising. Between 2020 and 2040, peak electricity demand is expected to grow nearly fourfold, requiring annual increases of around 7%. To meet this demand, the Philippines must expand its power generation capacity from 22,317 MW in 2019 to 114,601 MW by 2040.

These challenges affect various stakeholders. The Philippine government faces the difficult task of balancing energy security with its commitments under the Paris Agreement, which influences budget allocations during the transition to cleaner energy systems. The private sector struggles with fluctuating coal import prices and increasing regulatory pressures, while communities endure the health and environmental consequences of pollution and degradation.

Addressing these challenges requires reducing reliance on imported fuels and transitioning to cleaner energy technologies. Integrating nuclear energy into the country’s energy mix offers a strategic pathway toward a sustainable and secure energy future. This effort will necessitate strong collaboration between the government and the private sector to invest in innovative and sustainable energy projects.

However, public attitudes toward nuclear energy are often influenced by safety concerns and fears of accidents, shaped by historical incidents such as

Chernobyl, Fukushima, and Three Mile Island. Resistance is also driven by concerns about costs, nuclear waste management, and the potential for weapons proliferation. Despite these challenges, advancements in reactor design, stringent regulatory standards, and the development of safer technologies—such as Generation III and III+ reactors—have significantly improved safety, reduced waste, and mitigated risks, thereby fostering greater public confidence in nuclear energy.

Small Modular Reactor (SMR) technologies provide an opportunity to establish a more flexible and efficient energy system that aligns with current energy strategies. SMRs incorporate inherent and passive safety systems as part of a “defense in depth” approach. Their smaller size simplifies the design of safety systems, requiring less heat to be removed during emergencies, making them a highly adaptable and safer option for modern energy needs.

This study focused on the RTA of selected SMR technologies within the context of the Philippines, as the government emphasizes the transition to cleaner, more sustainable, and resilient energy systems. Specifically, it seeks to address the following questions:

1. What are the national policy goals, constraints, and requirements of the Philippines about the Philippine Nuclear Energy Program?
2. How should the weights be assigned to each RTA Key Element (KE), and what justifications can be provided based on the relevant national policy goals of the Philippines?
3. How can the selected SMR technology options from the IAEA’s Advanced Reactors Information System (ARIS) database be reviewed?
4. How should each SMR design be assessed against each RTA Key Element (KE), and what is the rationale for the assigned ratings?

A phased roadmap, starting with RTA studies and stakeholder consultations, followed by policy development and capability-building, and culminating in the deployment of selected nuclear technologies, ensures a well-structured implementation.

IV. OBJECTIVES OF THE STUDY

The Philippines faces major challenges in energy, including high electricity costs, reliance on imported fuels, and the need to meet climate goals. Nuclear energy offers a transformative solution by providing affordable, reliable, and clean power. However, choosing the right nuclear technology requires careful planning to ensure it fits the country's needs. The IAEA's RTA methodology can help the Philippines make informed decisions by evaluating nuclear technology options based on safety, cost, environmental impact, and sustainability.

This study aims to select the most appropriate nuclear technologies in the Philippines by applying the IAEA's RTA methodology. The specific objectives of this study are as follows:

1. Identify the national policy goals, constraints, and requirements of the Philippines in relation to the Philippine Nuclear Energy Program.

2. Determine the weights assigned to each RTA KE and provide justification based on the relevant national policy goals of the Philippines.

3. Evaluate the selected Small Modular Reactor (SMR) technology options from the IAEA's ARIS database, including BWRX-300, HTR-PM, NuScale, RITM-200, and, SMART.

4. Assess each SMR design against each RTA KE, providing a clear rationale for the assigned ratings.

By applying the RTA methodology, the Philippines' nuclear energy program will align with national policy goals, addressing energy security, environmental, and economic needs. The evaluation of SMR technologies will enable policymakers to select the safest and most viable options for the country, thereby fostering public trust. Transparent assessments of each technology against the KEs will support informed decision-making, enhance government accountability, and improve public acceptance of nuclear energy as a sustainable solution.

V. RATIONALE

Nuclear energy is a strong option for providing clean, zero-emission power to meet the growing electricity needs of the Philippines while helping the country meet its goals to reduce greenhouse gas (GHG) emissions. It also offers benefits such as more jobs, better energy security, and a cleaner environment. For policymakers, integrating nuclear energy offers multiple benefits. Economically, it can stimulate job creation in infrastructure development, operations, and maintenance while reducing electricity costs for businesses and households. It strengthens energy independence by decreasing reliance on imported fuels, enhancing the resilience and stability of the energy supply.

Replacing coal power can be helped by adding more nuclear power plants. New technology, especially SMRs, offers a cheaper and faster way to build nuclear plants than traditional ones. SMRs also use less fuel and could provide reliable electricity to remote areas.

Nuclear energy offers numerous benefits that make it a crucial component of a sustainable energy future. Environmentally, it produces significantly fewer greenhouse gas emissions than fossil fuels, helping combat climate change (Hilliard, 2014, p. 7). It provides energy security by offering a reliable and sustainable alternative to finite resources like coal and oil, ensuring long-term availability as global energy demands rise (Hilliard, 2014, p. 9). Advances in technology, such as Small Modular Reactors (SMRs), enhance safety, reduce costs, and allow for innovative applications like powering remote areas and desalination plants (Hilliard, 2014, pp. 18–22). Nuclear energy also supports a decentralized power grid, reducing vulnerabilities to cyberattacks and ensuring the resilience of critical infrastructure, including military bases (Hilliard, 2014, pp. 24–25). Economically, it creates jobs and fosters industrial growth while maintaining high safety standards through stringent regulations, particularly those set by the U.S. Nuclear Regulatory Commission (Hilliard, 2014, pp. 11–12). Additionally, nuclear power is a scalable and reliable complement to renewable energy, aiding in global efforts to achieve carbon neutrality (Hilliard, 2014, p. 13). These advantages highlight the potential of nuclear energy to meet both present and future energy needs sustainably and securely.

Nuclear energy plays a critical role in major nuclear power countries like the USA, France, Russia, China, and Canada by enhancing environmental safety, supporting economic growth, and mitigating urbanization-related challenges. It improves the load capacity factor by reducing greenhouse gas emissions and preserving biodiversity, making it a key tool for combating climate change. Nuclear energy provides a stable, cost-effective power supply, boosting industrial productivity and reducing reliance on fossil fuels. In urbanized areas, it helps mitigate environmental degradation through reliable and decentralized energy systems. Additionally, these nations influence global energy policies by exporting nuclear technology and expertise, reinforcing their leadership in sustainable energy development (Teng et al., 2023).

VI. SCOPE AND LIMITATIONS

This study focuses on the application of IAEA's RTA methodology to select the most suitable SMR technology design in line with the Philippine energy strategic framework. SMR engineering and design are usually completed after they have been approved for construction in a particular country and after undergoing regulatory reviews. Currently, only a limited number of SMR designs have been approved or are under construction, with the most active countries in this field being the USA and the Russian Federation. SMR development is also underway in Argentina, Brazil, Canada, China, France, India, Japan, the Republic of Korea, and South Africa. The large number of research centers involved has resulted in considerable variation in proposed reactor designs (Rowinski et al., 2015).

Larson (2024) highlighted two operational SMR designs: Russia's KLT-40S and China's HTR-PM. The KLT-40S, used in the floating nuclear power plant Akademik Lomonosov, delivers 70 MW of electricity and 50 Gcal/hr of heat, featuring a modular structure and robust safety systems. The HTR-PM, a high-temperature gas-cooled reactor, offers enhanced efficiency and inherent safety. These designs demonstrate the potential of SMRs to provide cost-efficient, flexible, and scalable solutions for diverse environments.

For this study, the SMR designs under review for electricity production include the American NuScale, the Korean SMART, the Russian RITM-200, the Chinese HTR-PM, and the Japanese-American BWRX-300. Most of these SMRs are feasible for deployment in the Philippines due to existing proposals and cooperative agreements with the respective design manufacturers. The Philippine government, in collaboration with private industry, has signed multiple agreements to evaluate the feasibility of SMR deployment, including those for the RITM-200, SMART, and

NuScale designs.

A comprehensive evaluation of these reactor technologies requires credible data and a deep understanding of SMR designs and the RTA methodology. The author conducted the evaluation, having completed the 2024 Reactor Training Program (RTP), organized by the Nuclear Reactor Operations Section (NROS), Nuclear Services Division (NSD), and the Philippine Nuclear Research Institute (PNRI). Held at the PNRI compound from April 15–26, 2024, this program included 60 hours of lectures and practical exercises on topics such as fundamental reactor concepts, radiation protection, reactor physics and engineering, nuclear safety, security and safeguards, emergency planning, and the application of the IAEA's RTA methodology.

VII. DESCRIPTION OF THE STUDY AREA

The Philippines is made up of over 7,000 islands and is located about 500 miles (800 km) east of Vietnam in Southeast Asia (Cullinane et al., 2024). The Institute for Economics and Peace (2019) reported that the Philippines is the most at risk from climate change. This is mainly because of its location. Climate change causes problems like rising sea levels, more extreme weather, higher temperatures, and heavy rainfall.

Human activities, especially releasing GHGs like carbon dioxide (CO_2), are the main cause of climate change (Petelo, 2021). In the Philippines, most GHG emissions come from the energy sector, with the rest from waste, industry, farming, and land use changes (USAID, 2024). In 2022, the country's total emissions were 135.7 million tons of CO_2 equivalent ($MtCO_2e$). Over half (56.2%) came from power generation, mainly from coal-fired plants, which produced 76.3 $MtCO_2e$ (Department of Energy, 2024).

To ensure stable, reliable, and affordable energy, the Department of Energy (DOE) is working toward a sustainable future by using different clean energy sources. Nuclear power is being explored as a long-term option to support the country's growth and sustainability goals (Department of Energy, 2024).

Currently, the Philippines does not use nuclear energy. However, after the 1973 oil crisis, the government built the two-unit Bataan Nuclear Power Plant. The first unit was finished in 1984 but never started because of financial problems and earthquake safety concerns. There was a plan to convert it to run on natural gas, but it was not possible, so the plant has been maintained but unused. In 2010, Korea Electric Power Corporation estimated that fixing the plant would cost about US$1 billion (World Nuclear Association, 2024).

In 2016, the DOE confirmed that nuclear power is a good option and could replace some coal power. The Philippine Energy Plan (2023–2050) aims to start using nuclear power by 2032 with at least 1,200 MW capacity. This would increase by another 1,200 MW by 2035 and 2,400 MW by 2050. The Nuclear Energy Program is expected to help train skilled workers, increase productivity, lower emissions, and offer an affordable way to reduce greenhouse gases. Nuclear energy can help meet the country's constant, large-scale power needs.

VIII. METHODOLOGY

The methodology for achieving the four key objectives of this study involves a combination of qualitative and quantitative approaches, including document analysis and comparative evaluations.

Figure 1. Conceptual framework

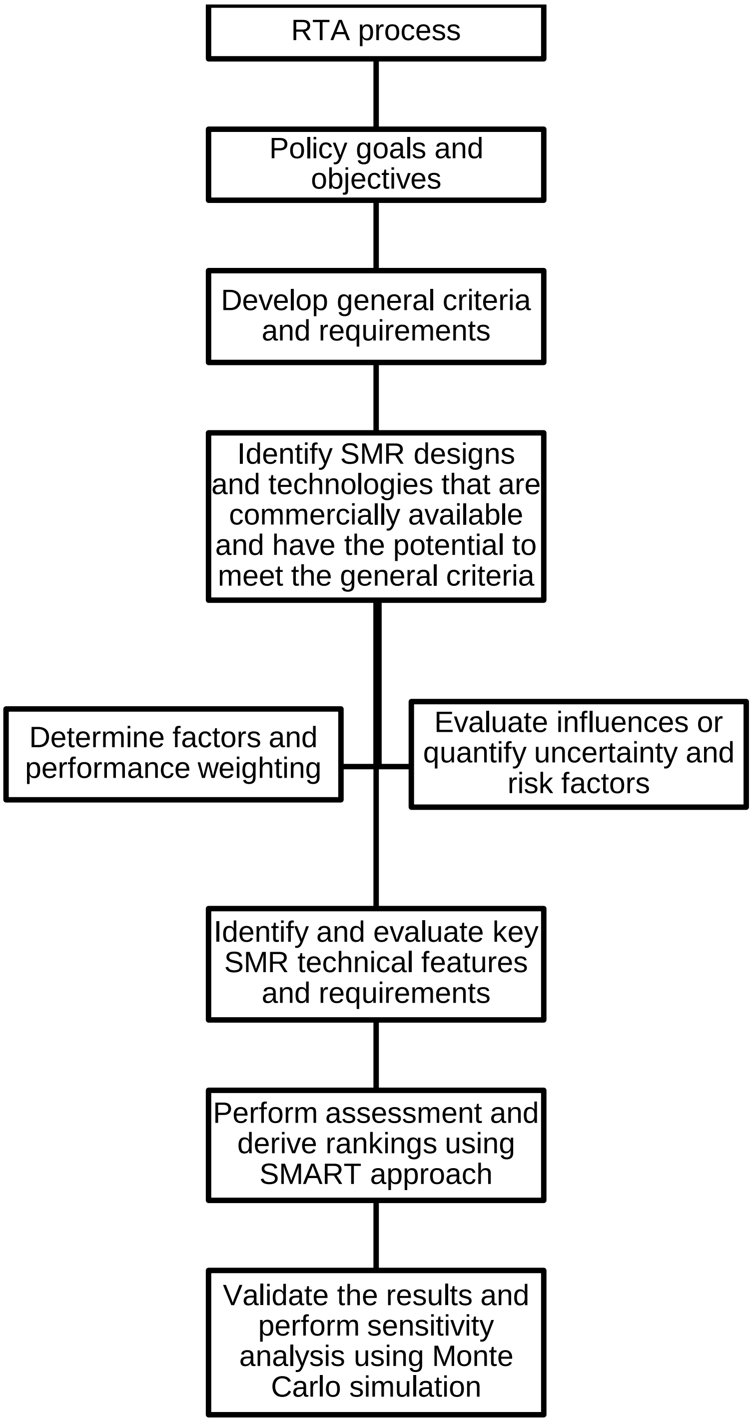
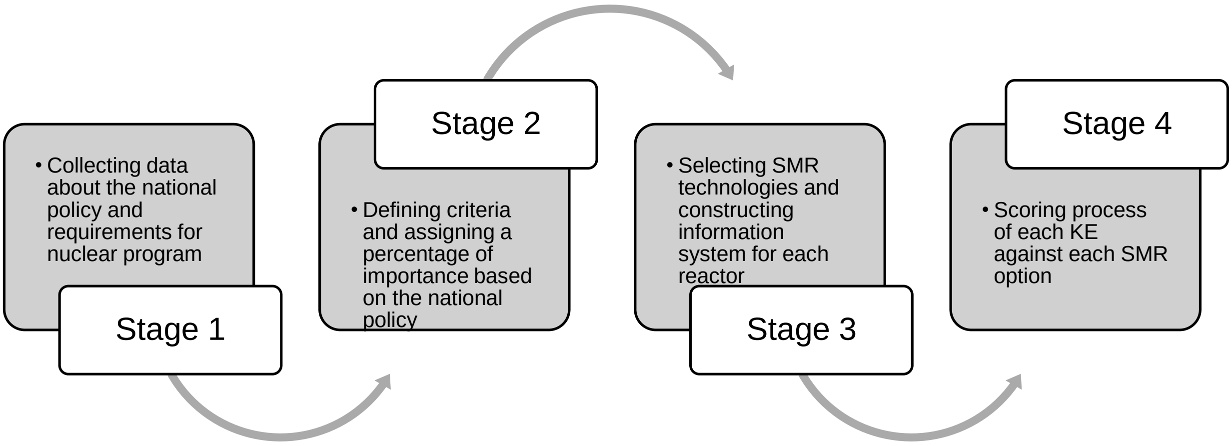


Figure 2. Reactor technology assessment's study plan



The RTA has several steps to check if SMRs are suitable for a country's nuclear program. The steps in the RTA process are shown in Figure 2. First, the Philippines' national nuclear policies and rules were reviewed to see if they support SMR use. Next, important criteria were checked to decide if SMRs could move forward in the project. These criteria include ten KEs shown in Figure 3. In the third step, detailed information was gathered about five SMR types: NuScale, SMART, HTR-PM, BWRX-300, and RITM-200, covering all important factors. Finally, each SMR was scored and ranked based on how important each factor is. The RTA tool calculates a weighted score by multiplying each score by its importance. These scores were then compared to find the best SMR option for the country.

Figure 3. Key elements of RTA

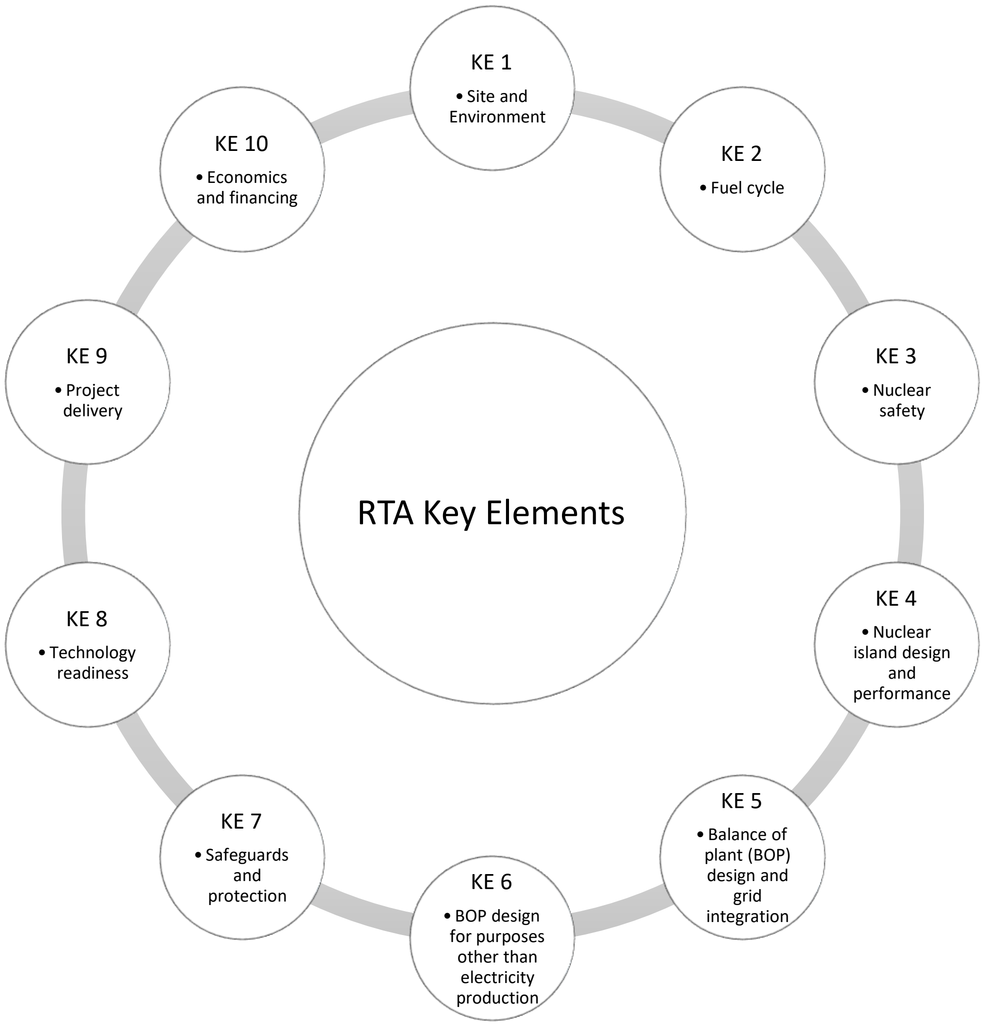
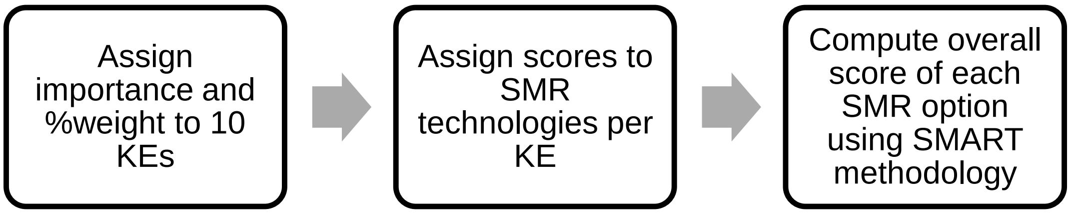


Figure 4. RTA method scoring process



Determining national policy objectives and requirements

To identify the national policy goals, constraints, and requirements of the Philippines in relation to the Philippine Nuclear Energy Program (PNEP), a comprehensive review of key national policy documents such as the Philippine Energy Plan (PEP) 2023–2050 was done. This document provides a foundation for understanding the country's energy security, sustainability goals, greenhouse gas emissions, economic growth, and disaster resilience.

The identified policy objectives were assigned relative importance weighting to each one. This was accomplished by reviewing the rank-ordered list (e.g. low, medium, and high) and matching the typical scoring for the applied RTA. The approach in RTA was to classify technology features that support each policy objective into KEs.

Assigning weights to each RTA KE based on the relevant national policy goals

To determine the relative importance of each RTA KE, a percent weight was used. The total point value for all KEs was 100%. The scoring was based on how well they support the country's energy goals. This process ensures that the evaluation framework reflects national priorities, such as reducing carbon emissions, ensuring energy security, and maintaining economic viability.

The RTA methodology is composed of ten KEs, each of which is necessary to assess whether SMRs are suitable for particular nuclear power projects. Each KE is summarized as follows:

KE1. Site and environment – focuses on site-related factors.

KE2. Fuel Cycle – covers all steps in producing nuclear energy, from fuel processing to reactor operation.

KE3. Nuclear Safety – focuses on safe operation to protect workers, the public, and the environment from radiation.

KE4. Nuclear Island – looks at site-specific nuclear design, especially for SMRs.

KE5. Balance of Plant and Grid Integration – deals with connecting the plant to the site and power grid for safe and reliable operation.

KE6. Balance of Plant for Non-Electric Uses – considers how the plant supports non-electric needs based on the country's requirements.

KE7. Safeguards and Protection – covers measures to prevent theft, sabotage, or unauthorized access.

KE8. Technology Readiness – evaluates how proven and experienced the SMR technology is, especially for new designs.

KE9. Project Delivery – assesses the ability to build and deliver SMRs on time and within budget.

KE10. Economics and Financing – looks at the costs of building nuclear plants, which can vary by site; SMR economic data is still limited.

The RTA method allows assigning different importance levels to each KE, enabling a detailed evaluation tailored to each country and project.

Evaluation of selected SMR technologies

The evaluation of SMR technology options was performed using the significant design information available in the IAEA's ARIS database, other reliable public sources, third-party studies, vendor websites, licensing submissions, and environmental impact assessments. A detailed assessment of each SMR design was based on criteria such as technical feasibility, capacity, fuel type, operational safety features, and compatibility with the Philippine energy infrastructure. Key performance indicators were identified to measure each design’s suitability for the country's energy needs.

SMRs are designed to be built in factories as modules and then transported to the site. This method improves efficiency and reduces construction time and costs. Their designs are usually finalized after passing regulatory approval. Only a few SMR models are approved or under construction, including NuScale (USA), SMART (Korea), HTR-PM (China), RITM-200 (Russia), and BWRX-300 (Japan/USA). The RTA methodology was used to conduct a comparative analysis across five distinct SMR technology designs, namely NuScale, SMART, HTR-PM, BWRX-300, and RITM-200.

Grading each SMR design against the RTA KEs

The grading process evaluated 10 KEs for each of the five SMR designs in the country. This study used the simple multi-attribute rating technique (SMART), a decision-making method created by Edward in 1997 (Siregar et al., 2017). The total score for each SMR option was calculated by adding up the scores for each KE, each multiplied by its assigned weight. Justifications for the ratings were provided, explaining how each design met or exceeded the requirements of the KEs. The overall scores of selected SMRs are then compared to determine which option is best for the country.

Formula:

SMR technology overall score = Σ (Weight of KE i * Rating of KE i)

Assign weights:

The most important step was to accurately determine the weight of each KE based on national policies.

Scaling:

Ratings for each KE are based on a 5-point scoring system to allow for comparison.

Table 1

Setting the Range of a 5-point Scoring System

Score	1	2	3	4	5
Range	<80%	80 to 84%	85 to 89%	90 to 95%	>95%
Description	Little extent/ not acceptable	Lesser than medium extent, but greater than a little extent	Medium extent	Greater than medium extent, but not to a large extent	Large extent

Statistical analysis

To ensure the robustness of the RTA methodology, a sensitivity analysis using Monte Carlo simulation was conducted to examine how changes in the weighing of KEs might affect the rankings. This analysis was done to understand which KE has the most significant impact on the output by systematically varying each input while holding others constant. Employing this technique iteratively and analyzing the results can provide a transparent and objective basis for decision-making (Thevapalan, 2024).

IX. RESULTS

National policy goals, constraints, and requirements

The Philippine Nuclear Energy Program (PNEP) aims to explore how nuclear energy can support a sustainable energy transition, following the Philippine Energy Plan (PEP) 2023–2050. The PNEP helps the Department of Energy (DOE) achieve its goals of providing secure, stable, reliable, and affordable energy for the country.

The DOE uses a technology-neutral approach to develop clean energy and diversify sources, including nuclear power as a long-term option. The DOE is actively studying nuclear energy to see if it can help support the country’s sustainable development and growth. The national policy objectives are identified to describe in a specific manner what the PNEP intends to achieve. Table 2 represents a breakdown of national strategies and requirements and their relative importance.

The PNEP represents a transformative step in the nation’s pursuit of a clean, secure, and resilient energy future. While challenges such as financial constraints, regulatory development, and infrastructure upgrades remain, the program offers significant opportunities to meet rising energy demands, reduce environmental impacts, and enhance the country's energy independence. By integrating nuclear energy into its strategy, the Philippines is positioning itself as a forward-looking nation ready to embrace innovative solutions to its energy challenges.

Table 2

Philippine national policy objectives and their respective importance for electricity production using nuclear energy

Relative importance	Policy Objectives
High	National and international legal and regulatory frameworks
High	Promoting stable and reliable power systems
High	Stable and affordable energy source to spur industrial and economic development
High	Establish and maintain nuclear safety, security, and safeguards
High	Transitioning to low-carbon energy systems in compliance with the country's Nationally Determined Contribution (NDC) to the Paris Agreement and addressing the projected decline of coal power plants
High	Minimal effect on the environment, including mitigation of GHG
Medium	Strengthening energy infrastructure against climate and disaster risks
Medium	Ensure sustainability through assurance of components supply over the facility's lifetime
Medium	Addressing the Philippines' rapidly growing population and increasing urbanization
Medium	Adaptability to existing grid systems and geographic constraints
Medium	Operate independently in remote or isolated locations

Medium	Minimize construction and financing costs by ensuring that the proposed construction schedule is met
Low	Long-term human capital investment
Low	Leveraging public-private partnerships (PPPs), international financing, and government allocations under the Clean Energy Finance Framework

Assigning weights to each RTA KE based on the relevant national policy goals

National nuclear project goals must guide the development of user criteria for the RTA. The RTA's purpose is to compare reactor technologies and identify the best option to meet these goals. After defining the objectives and their importance, the relative weights of the 10 RTA key elements (KEs) are determined. The weight that each KE holds is significant in identifying the SMR technology that can best deploy in the Philippines.

Table 3

Weight of each RTA KE based on the PNEP objectives

Key Elements	Policy objectives covered	Relevance in weight percentage
KE1. Site and environment	Minimal effect on the environment, including mitigation of GHG Strengthening energy infrastructure against climate and disaster risks Addressing the Philippines' rapidly growing population	19%

	and increasing urbanization Adaptability to existing grid systems and geographic constraints Operate independently in remote or isolated locations	
KE2. Fuel cycle	Promoting stable and reliable power systems Stable and affordable energy source to spur industrial and economic development Ensure sustainability through assurance of components supply over the facility’s lifetime	9%
KE3. Nuclear safety	National and international legal and regulatory frameworks Establish and maintain nuclear safety, security, and safeguards Strengthening energy infrastructure against climate and disaster risks	14%
KE4. Nuclear island design and performance	Promoting stable and reliable power systems Stable and affordable energy source to spur industrial and economic development Transitioning to low-carbon energy systems in compliance with the country’s Nationally Determined Contribution (NDC) to the Paris Agreement and addressing the projected decline of coal power plants Adaptability to existing grid systems and geographic constraints Operate independently in remote or isolated locations	18%

KE5. BOP design and grid integration	Adaptability to existing grid systems and geographic constraints	3%
KE6. BOP design for purposes other than electricity production	Not applicable	0%
KE7. Safeguards and protection	National and international legal and regulatory frameworks Establish and maintain nuclear safety, security, and safeguards	11%
KE8. Technology readiness	Promoting stable and reliable power systems Stable and affordable energy source to spur industrial and economic development Transitioning to low-carbon energy systems in compliance with the country's Nationally Determined Contribution (NDC) to the Paris Agreement and addressing the projected decline of coal power plants	17%
KE9. Project delivery	Ensure sustainability through assurance of components supply over the facility's lifetime Minimize construction and financing costs by ensuring that the proposed construction schedule is met	7%

KE10. Economics and financing	Long-term human capital investment Leveraging public-private partnerships (PPPs), international financing, and government allocations under the Clean Energy Finance Framework	2%

Evaluation of selected SMR technologies

The DOE is considering adding nuclear power to the Philippines' energy mix. To ensure a coordinated government effort, the Nuclear Energy Program Implementing Organization (NEPIO) formed the NEP Inter-Agency Committee (NEP-IAC) through Executive Order 116 in 2020. The DOE chairs the NEP-IAC, with the DOST as vice-chair. The committee includes 24 government agencies organized into six sub-committees, each addressing specific infrastructure issues based on the IAEA Milestone Approach.

The DOE plans to build eight 150-MW SMRs to add 1,200 MW of nuclear capacity by 2032 (Crismundo, 2024). The clean energy scenario also forecasts an additional 1,200 MW by 2035 and 2,400 MW by 2050. Around 12 sites in the western Philippines are being studied for future nuclear plants. The descriptions of the selected SMR technologies that will be assessed in this investigation are given in Table 4.

Table 4

Technical data summary of selected SMR technology options

Parameters	R#1 (BWRX-300)	R#2 (HTR-PM)	R#3 (NuScale)	R#4 (RITM-200N)	R#5 (SMART)
Design Org	GE-Hitachi and Hitachi GE Nuclear Energy	JAEA	NuScale Power LLC.	JSC "Afrikantov OKBM"	KAERI
Coolant	H_2O	He	H_2O	H_2O	H_2O
Moderator	H_2O	Graphite	H_2O	H_2O	H_2O
Type	BWR	GCR	PWR	PWR	PWR
Purpose	Commercial – Electric/Non-Electric	Experimental	Commercial – Electric/Non-Electric	Commercial – Electric/Non-Electric	Commercial – Electric/Non-Electric
Design Status	Detailed design	Operational	Under regulatory review	Detailed design	Detailed design
Country	United States of America	China	United States of America	Russian Federation	Korea, Republic of

Table 5

Detailed specification of selected SMRs categorized by RTA key elements

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 1. Site and environment	Designed for inland/coastal sites; underground reactor building improves protection; seismic design withstands 0.3 g; emergency planning zone of 0.350 km	Inland, modular units allow flexible deployment; Best suited for water-scarce areas; seismic resistance up to 0.2 g may need enhancement	Designed for inland sites; ideal for isolated or small grids; seismic-resistant up to 0.5 g; aligns with distributed energy needs	Ideal for remote, off-grid areas and maritime use; can withstand 20-ton aircraft at a speed of 215 m/s; seismic-resistant up to 0.3 g; emergency planning zone of 5 km	Designed for inland/coastal sites; flexible cooling options and minimal land use; seismic design withstands 0.3 g

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 2. Fuel cycle	Uses LEU fuel with 12-24 month cycle; Zircalo-2 fuel cladding material, 240 fuel units, spent fuel racks equivalent to 8 years of refueling operations plus a full core off-load and new fuel storage	Once-through cycle, high burnup (90 MWd/kgHM), TRISO fuel; continuous fuel loading and discharging; spent fuel for reprocessing	LEU fuel, 18-month cycle, standard PWR fuel assembly; 50 – 55 MWd/kg core discharge burnup; 10 years of spent fuel storage	LEU fuel, 60-month cycle; 42CrNiMo or Zr fuel cladding material; 54 MWd/kgHM pin burnup; 199 fuel units; 30 years of spent fuel pool capacity	LEU fuel, 30-month cycle; spent fuel is permanently disposed of without recycling; 30 years spent fuel pool capacity

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 3. Nuclear safety	Passive safety systems; natural circulation cooling; core damage frequency <1E-7/reactor-year	Intrinsically safe pebble bed design; high containment of fission products; passive heat removal	Advanced passive cooling; natural convection; robust seismic resistance	Passive cooling; natural circulation; multiple containment barriers	Passive safety with indefinite self-cooling; below-ground containment provides added resilience

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 4. Nuclear island design and performance	Simplified BWR design, 300 MWe, uses established BWR fuel; 60-year design life; 95% lifetime capacity factors; 10920 m^2 plant footprint, 27000 m^2 site footprint; load-following capability (50-100%), 0.5% per minute load following range and speed; does not support house load operation	Modular HTGR, 200 MWe (2x100 MWe modules); 40-year design life; 256,100 m^2 plant footprint	Modular PWR, 77 MWe per module, scalable up to 12 modules; 60-year design life; 95% lifetime capacity factor	Modular PWR, scalable with multi-unit configurations of up to 12 reactors (600 MW total); 60-year design life; 76% lifetime capacity factor; 120,000 m^2 plant footprint; load-following capability (30 – 100%), 6% per minute load following range and speed	Modular PWR, highly scalable with 12-module configurations (up to 924 MW); 60-year design life; 95% lifetime capacity factor; 10,000 m^2 plant footprint; load-following capability (20 – 100%), 5% per minute load following range and speed

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 5. Balance of plant (BOP) design and grid integration	Standard turbine island; designed for load following	Steam Rankine cycle, potential for process heat applications	Rankine cycle with helical steam generators, flexible grid integration	Rankine cycle with a vertical, once-through steam generator	Rankine cycle with once-through helical steam generator
KE 6. BOP design for purposes other than electricity production	Can support district heating & industrial processes	Designed for process heat applications, cogeneration	Suitable for process heat and hydrogen production	Not applicable	Steam supply for oil sand sites

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 7. Safeguards and protection	Standard BWR safeguards, underground design enhances security; spent nuclear material (SNM) material control	Large spent fuel volume and high burnup reduce proliferation risk; reactor building forms robust barriers against sabotage attacks	Standard LWR safeguards, small modular design enhances security	IAEA inspections may be performed in a shortened format because core refueling is once every 5 – 6 years; surveillance equipment; no partially burned-up FA reshuffling; conventional physical protection	KAERI established a safeguards approach and submitted a Safeguards Technical Report to the IAEA in 2023

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 8. Technology readiness	10th-generation BWR, pre-licensing and license to construct (2025) in Canada; commercial deployment expected by 2029	First HTR-PM operational in China since 2021	NRC-certified design, first plant expected in 2029	Detailed design; plans to use as the basis for the first small ground-based nuclear power plant in Ust-Kuiga, Yakutia, aiming for commissioning by 2028	Detailed design; KAERI is actively exploring potential markets including collaborations with countries like Canada

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 9. Project delivery	Standardized design for factory construction, ~4 years of construction time	50-month construction time for the first plant, modular scalability	Factory-fabricated modules, scalable deployment	No data was provided for the construction time; the Russian Federation is implementing a pilot-wide project titled "Construction of a small-sized nuclear power plant based on the RITM-200N Reactor Plant"	36-month construction time

IAEA RTA's Key Elements	BWRX-300	HTR-PM	NuScale	RITM-200N	SMART
KE 10. Economics and financing	USD 4,333/kW; competitive due to simplified modular design and proven technology	USD 4,500/kW; cost-effective for cogeneration in the Chinese market	Estimated at USD 5,000/kW; viable for small, remote grids	No reliable cost data but optimized for isolated regions and remote deployment	USD 20,000/kW; cost increases have reduced initial attractiveness

R#1 – Boiling Water Reactor X-300 (BWRX-300)

The BWRX-300 is offering a compact, 300 MWe power output advanced technology option. Leveraging over 40 years of boiling water reactor (BWR) experience, this 10th-generation design incorporates proven features such as natural circulation cooling and advanced passive safety systems. Its reliance on natural phenomena for cooling eliminates the need for complex active components, simplifying operation and maintenance. With a load-following capability of 50-100% and a ramp rate of 0.5% per minute, it is well-suited to meet fluctuating energy demands (GE Hitachi Nuclear Energy, 2023).

The reactor uses uranium dioxide (UO2) fuel with up to 4.95% enrichment, which aligns with established supply chains and enables a high discharge burnup of ~50 MWd/kgHM for better fuel efficiency. Safety is a core feature, with the reactor employing a defense-in-depth approach comprising five levels of safety, ensuring resilience against operational anomalies and accidents. Its passive safety systems, such as isolation condensers and large water reservoirs, allow it to remain safe for seven days without operator intervention or external power. The design boasts a low core damage frequency of <1E-7/reactor-year, underscoring its robust safety performance (GE Hitachi Nuclear Energy, 2023).

The BWRX-300 has a modular design and flexible siting requirements, including suitability for both coastal and inland locations. It offers multiple cooling options and is designed to interface seamlessly with grid systems operating at 50/60 Hz, while its seismic design can withstand an SSE of 0.3 g, addressing the Philippines' earthquake-prone conditions (GE Hitachi Nuclear Energy, 2023).

The BWRX-300 is the reactor with the greatest declared commercial sophistication. The first plant is expected to begin operation in Canada in 2028

(PricewaterhouseCoopers LLP, 2021), while in Poland the first plant could become operational in 2029 (KPMG International, 2023). It has an estimated manufacturing and construction cost of USD 4,333/kW.

R#2 – High-Temperature GCR - Pebble-Bed Module (HTR-PM)

The HTR-PM is a modular high-temperature gas-cooled reactor producing 200 MWe from two reactor modules linked to one turbine, with potential for expansion. It uses helium coolant, graphite moderator, and TRISO-coated LEU fuel enriched to 8.5%, allowing high fuel burnup and strong containment of fission products. Safety is built-in with passive heat removal and negative reactivity, reducing the need for complex safety systems.

Designed for simplicity and resilience, the HTR-PM can passively cool decay heat without external power, making it suitable for water-scarce areas. Its seismic design withstands up to 0.2 g, which may require upgrades for the Philippines' earthquake risk.

China’s twin HTR-PM units, producing 210 MWe, began commercial operation in December 2023. They co-generate high-temperature steam and electricity, offering a cost-effective alternative to natural gas and coal, especially for the petrochemical industry. The installation cost is about USD 4,500/kW (Alonso et al., 2023).

R#3 – NuScale Power Module

The NuScale Power Module™ (NPM) is a 77 MWe light-water SMR using low-enriched uranium (LEU) fuel with a proven 17x17 PWR design. A plant can host up to 12 modules, reaching a total capacity of 924 MWe. It operates on an 18-month fuel cycle with onsite spent fuel storage for 60 years.

NuScale prioritizes safety through passive systems that allow indefinite cooling without power or operator action. Its underground containment pool serves as a heat sink and radiation shield, and the design meets seismic standards up to 0.5 g—suitable for earthquake-prone areas. It includes both air and water cooling options and supports grid flexibility.

NuScale’s first SMR is planned for the Utah Associated Municipal Power Systems or UAMPS in the U.S., targeted for 2029. However, costs have risen to an estimated USD 20,000/kW (Smith & Lacey, 2023).

R#4 – RITM-200N

The RITM-200N was developed by Rosatom and was primarily designed for small-scale energy production in remote or isolated regions. Based on the reactors used in Russian nuclear-powered icebreakers, it is a compact pressurized water reactor (PWR) with a nominal capacity of 50 MW per unit. While relatively small, it can be deployed in multi-unit configurations of up to 12 reactors, providing a scalable output of up to 600 MW. This makes it suitable for smaller grids or off-grid areas, particularly those with fluctuating power demands or limited access to conventional energy sources. The reactor uses low-enriched uranium (LEU) as fuel, with a refueling interval of up to 7 years, ensuring long-term operational efficiency and minimal fuel handling requirements.

The RITM-200N incorporates advanced safety features, including passive safety systems that do not rely on external power or active mechanical systems for cooling and shutdown. This design, combined with natural circulation cooling and multiple containment barriers, ensures the reactor's safety even in emergencies.

Additionally, it is seismic-resistant, an important consideration for earthquake-prone regions like the Philippines. The reactor's modular nature and long operational cycle make it ideal for deployment in remote areas, where infrastructure investment is often challenging.

The RITM-200N could provide stable baseload power that would help address grid stability issues, especially in areas that rely heavily on intermittent renewable energy. Furthermore, its smaller size and scalability would allow for integration into smaller, distributed grids, making it particularly suited for the Philippines' many islands and remote communities.

Russian state nuclear corporation Rosatom signed a memorandum of understanding with Guinea to assess the potential use of floating nuclear power plants in the country (Kraev, 2024). However, no construction cost data is currently available for the RITM-200N.

R#5 – System-Integrated Modular Advanced Reactor (SMART)

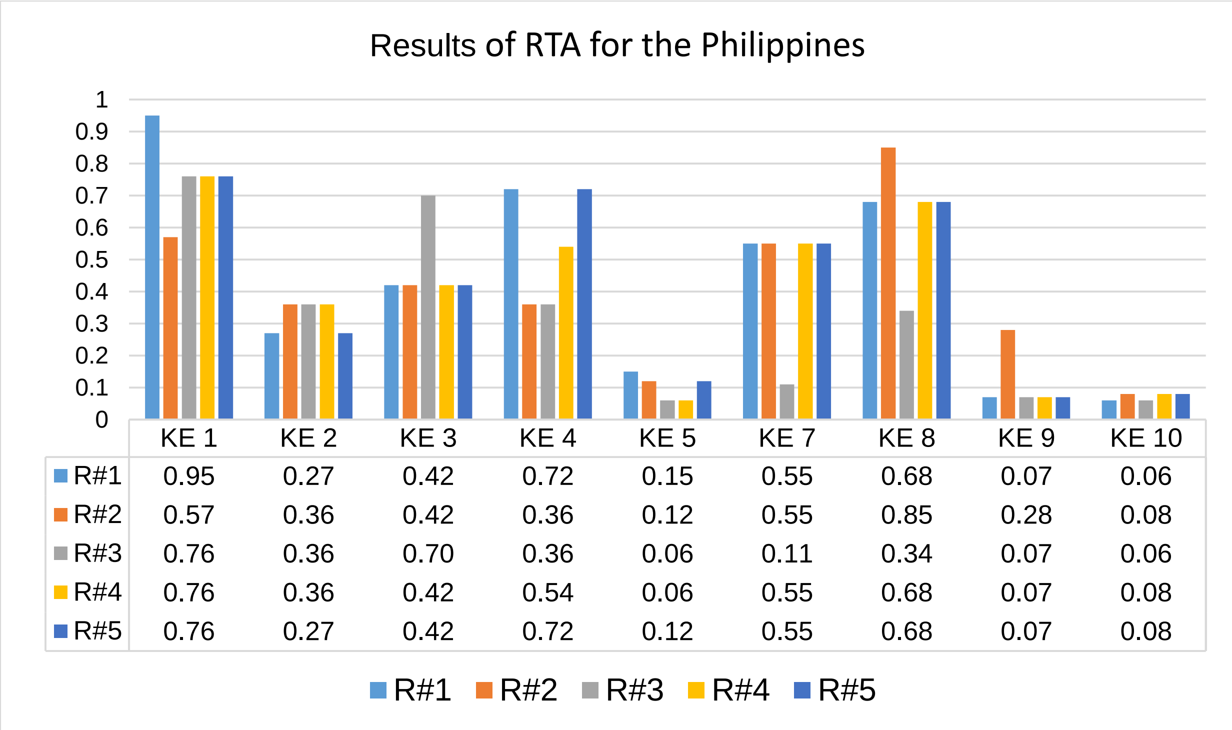
The SMART (System-integrated Modular Advanced Reactor) was developed by South Korea's KAERI. It was designed for efficient and flexible energy production in smaller-scale or remote settings. With a capacity of 100 MW, it is well-suited for isolated grids or areas with fluctuating power demands, and its modular design allows for easy scaling by adding multiple units at a site. The reactor uses low-enriched uranium (LEU) as fuel, with 18-month refueling cycles, optimizing fuel efficiency and reducing operational disruptions. SMART's advanced safety features include passive cooling systems, which rely on natural convection and gravity for heat dissipation during emergencies, eliminating the need for external power or active systems. The reactor's seismic resistance also makes it suitable for earthquake-prone regions like the Philippines. In terms of compatibility, SMART's small capacity and modular design align well with the Philippines' need for reliable, low-carbon energy sources, particularly for remote and off-grid communities. While its integration into the national grid could complement renewable energy sources, regulatory development and economic considerations, including cost and public acceptance, would be critical to successful deployment. If these challenges are addressed, SMART could help diversify the Philippines' energy mix, enhance grid stability, and contribute to a sustainable energy future.

In 2019, South Korea and Saudi Arabia agreed to jointly commercialize SMART, aiming for design approval and future deployment. Although no SMART unit has been built yet, its estimated construction cost is around USD 5,000/kW (Han & Roh, n.d.; World Nuclear Association, 2024d).

Assessment of each SMR design against each RTA KE

This study used the Simple Multi-Attribute Rating Technique (SMART) to assess SMR options based on KEs weighted according to national goals. Results from the RTA, illustrated in Figures 5 and 6 and detailed in Table 4, show that the BWRX-300 is the most suitable option for the Philippines. It had an overall highest score of 3.87. It offers strong site-specific features, including a seismic design of 0.3 g and a compact 0.35 km emergency planning zone. Given the Philippines' vulnerability to natural disasters due to its geographical location, the consideration of site and environmental factors plays a crucial role in ensuring safety, resilience, and sustainability in the deployment of SMR. SMART closely trailed behind BWRX-300 and received an overall score of 3.67 across all 10 KEs. SMART achieved the highest scores in KE4 (nuclear island), KE7 (safeguards and protection), and KE10 (economics and financing) due to its 95% lifetime capacity factor, 60-year design life, established safeguards approach, and reduced maintenance needs. In the third place was HTR-PM which obtained an overall score of 3.59. This reactor secured the highest scores in KE2 (fuel cycle), KE7 (safeguards and protection), KE8 (technology readiness), KE9 (project delivery), and KE10 (economics and financing), as it stands out as the only operational SMR design among the evaluated options. However, HTR-PM received a low number of points in KE1 (site and environment), KE3 (nuclear safety), and KE4 (nuclear island) due to low seismic design, short design life, and unavailability of a reprocessing plan for long-term spent fuel. The RITM-200N ranked fourth, trailing the HTR-PM by only 0.07 points. However, this reactor design received the lowest scores in KE3, KE5, and KE9 due to its mixed active/passive safety approach, lower net power output, and undefined project schedule. NuScale, despite its robust safety program encompassing all five levels of defense-in-depth and a fully passive safety approach, received the lowest overall rating of 2.82. It ranked lowest in six key elements (KE4, KE5, KE7, KE8, KE9, and KE10), primarily attributed to its design still being under regulatory review.

Figure 5. RTA results for the Philippines



	KE 1	KE 2	KE 3	KE 4	KE 5	KE 7	KE 8	KE 9	KE 10
R#1	0.95	0.27	0.42	0.72	0.15	0.55	0.68	0.07	0.06
R#2	0.57	0.36	0.42	0.36	0.12	0.55	0.85	0.28	0.08
R#3	0.76	0.36	0.70	0.36	0.06	0.11	0.34	0.07	0.06
R#4	0.76	0.36	0.42	0.54	0.06	0.55	0.68	0.07	0.08
R#5	0.76	0.27	0.42	0.72	0.12	0.55	0.68	0.07	0.08

Table 6

Final scoring of 5 SMRs for the Philippines

Reactor Type	RTA Results
R#1 (BWRX-300)	3.87
R#2 (HTR-PM)	3.59
R#3 (NuScale)	2.82
R#4 (RITM-200N)	3.52
R#5 (SMART)	3.67

Statistical analysis

A Monte Carlo simulation was conducted to evaluate the sensitivity of the overall score of the BWRX-300 reactor design when 5% and 15% variations were applied to the score of one KE. The results revealed that KE1 exhibited a high relative standard deviation for both levels of variation, indicating that minor fluctuations in site and environmental parameters can significantly impact the overall score during the RTA scoring process. For a 5% variation in the KE score, the overall score ranged from a minimum of 3.70 to a maximum of 4.07. Similarly, for a 15% variation, the overall score ranged from a minimum of 3.37 to a maximum of 4.33. These findings underscore the importance of accurate assessment and management of site and environmental parameters to ensure reliable and robust scoring outcomes for the BWRX-300 design.

Table 7

Monte Carlo simulation results for examining the impact of 5% variation in specific KE score on the overall score of BWRX-300

Key elements	Average overall score	Minimum overall score	Maximum overall score	Standard deviation	Relative standard deviation
KE1	3.87	3.70	4.07	0.05	1.24
KE2	3.87	3.83	3.92	0.01	0.35
KE3	3.87	3.80	3.94	0.02	0.55
KE4	3.87	3.75	3.98	0.04	0.92
KE5	3.87	3.84	3.90	0.01	0.20
KE7	3.87	3.78	3.96	0.03	0.71
KE8	3.87	3.75	3.97	0.03	0.87
KE9	3.87	3.86	3.88	0.00	0.09
KE10	3.87	3.86	3.88	0.00	0.08

Table 8

Monte Carlo simulation results for examining the impact of a 15% variation in specific KE score on the overall score of BWRX-300

Key elements	Average overall score	Minimum overall score	Maximum overall score	Standard deviation	Relative standard deviation
KE1	3.87	3.37	4.33	0.14	3.63
KE2	3.87	3.74	3.99	0.04	1.04
KE3	3.87	3.65	4.07	0.06	1.57
KE4	3.87	3.50	4.20	0.11	2.75
KE5	3.87	3.79	3.94	0.02	0.58
KE7	3.87	3.61	4.14	0.08	2.17
KE8	3.87	3.53	4.22	0.10	2.58
KE9	3.87	3.84	3.90	0.01	0.27
KE10	3.87	3.84	3.91	0.01	0.24

X. ANALYSIS AND DISCUSSION

The energy framework of the Philippines is transforming alignment with the global energy transition. This shift encompasses the diversification of energy sources and the potential adoption of nuclear power, particularly through SMRs, as a long-term energy solution. The Philippine DOE is considering constructing eight 150-MW SMRs by 2032, with projections of additional capacities reaching 1,200 MW by 2035 and 2,400 MW by 2050 (Crismundo, 2024).

SMRs are different from traditional nuclear reactors mainly because they are "small" in size and "modular" in design. "Small" means their power output is usually up to 300 MWe, and "modular" means their parts are built in factories and then transported to the site for assembly. This makes them easier to scale and requires less space.

The U.S. Department of Energy supports SMRs due to their safety and economic advantages, which include:

1. Passive/inherent/safety-by-design safety systems, which do not require an operator or control system action;
2. Lower amount of radioactive material;
3. Simpler design that removes some possible accidents;
4. Smaller emergency planning areas;
5. Below-grade construction of the reactor;
6. Flexibility to add reactor units;
7. Lower investment and financial risk;
8. Potential replacement of old coal plants;
9. Use of local materials and factories;
10. Flexible power supply for different grid needs;

11. Easy transport of parts from the factory to the site; and

12. Better protection from natural disasters and attacks due to below-ground design.

A nuclear core meltdown, the most severe accident scenario for nuclear plants, can lead to significant radioactive leakage and long-term environmental contamination (Pedersen, 2007). The two primary causes of core meltdown are reactivity accidents and loss-of-coolant accidents (LOCA) (Murakami & Anbumozhi, 2021). The inherent safety features of SMRs are specifically designed to mitigate these risks. Their smaller reactor cores reduce the amount of hazardous material, thereby limiting the potential release of radioactive substances during accidents. Moreover, SMRs rely on natural convection for cooling, eliminating dependence on mechanical systems, which further enhances safety. SMRs are designed with advanced safety features that eliminate the need for large evacuation zones. In emergencies, they can shut down and cool without operator action, backup power, pumps, or extra water (Conca, 2018). This simplified safety design reduces both costs and risks compared to traditional reactors.

Unlike renewable sources such as solar and wind, which are affected by weather and require large land areas, SMRs offer consistent, compact, and reliable energy. Solar and wind farms may impact land use and ecosystems, while hydropower can flood large areas (Burrows, 2023; Union of Concerned Scientists, 2008). SMRs are transportable and suitable for remote or off-grid areas, making them a strong complement to renewables. They also support hybrid systems that improve energy reliability, especially in high-demand zones (La Camera, 2025; IRENA, 2025). While SMRs have higher upfront costs than renewables, they offer long-term economic benefits through stable operation and low emissions, aligning with climate goals (Shwartz, 2022; Sagoff, 2022).

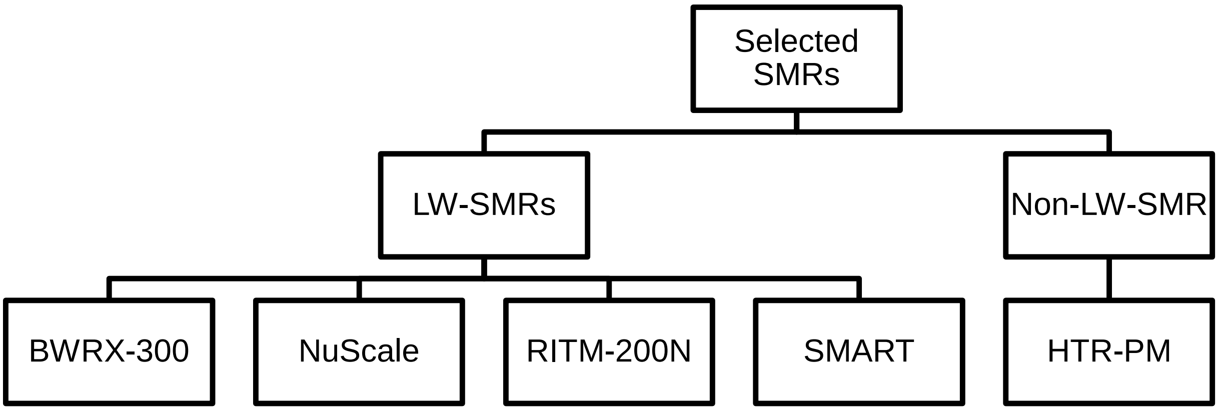
In the Philippines, over half of the electricity relies on imported coal. With the moratorium on new coal plants, SMRs are being considered as clean alternatives. SMRs are particularly suited for isolated islands without grid access. The government is revising its laws and policies to support nuclear safety, security, and safeguards (Trajano, 2022).

The DOE has identified 15–16 possible SMR sites, including Palawan and Sulu. A 100 MWe SMART SMR feasibility study is also planned in Cagayan with Korean collaboration. Meralco has proposed pilot SMR sites in Rizal, Bulacan, and near Malacañang (World Nuclear Association, 2024b; Mercurio, 2023).

The Philippine Nuclear Research Institute (PNRI) leads nuclear education and public awareness programs, working with schools, agencies, and private groups. Supported by DOE-NEPIO, PNRI develops nuclear technologies that meet national needs while ensuring safety standards (PNRI, 2021).

This study groups SMRs into two categories: Light Water SMRs (Gen III+) and Non-Light Water SMRs (Gen IV). Gen IV reactors are noted for better safety, lower waste, and higher efficiency.

Figure 6. Selected SMRs are categorized based on coolant type



The development of a nuclear power program requires meticulous planning and preparation. The IAEA developed the RTA to establish the requirements and criteria for initiating a nuclear power program. The first step is to identify the Philippines' national energy requirements and nuclear policy objectives to select the most suitable reactor technology. High-priority objectives include establishing robust legal and regulatory frameworks at both national and international levels, ensuring stable and reliable power systems, and providing affordable energy to foster industrial and economic growth. Additional key goals include maintaining nuclear safety, security, and safeguards; transitioning to low-carbon energy systems to meet Paris Agreement commitments; and mitigating environmental impacts, particularly greenhouse gas emissions. This balanced approach addresses immediate energy demands while promoting economic growth, environmental sustainability, and long-term resilience.

The next step in the RTA involves assigning weights to each Key Element (KE) based on these national policy objectives. The highest weights were assigned to KE1 (site and environment, 19%), KE4 (nuclear island design and performance, 18%), and KE8 (technology readiness, 17%). KE1 emphasizes minimizing environmental impact, mitigating greenhouse gas emissions, and ensuring geographic adaptability and climate resilience. KE4 focuses on stable and affordable energy solutions that support economic growth and align with low-carbon energy transitions. KE8 reflects the importance of proven, reliable technologies that ensure sustainable and affordable energy systems. Lower weights were assigned to KE5 (BOP and grid integration, 3%) and KE10 (economics and financing, 2%), while KE6 (BOP design for non-electricity production) was deemed inapplicable.

The SMART methodology was used in this study to evaluate SMRs due to their flexibility and simplicity in decision-making. Unlike more complex methods such as the Analytic Hierarchy Process (AHP), which can become computationally intensive, SMART is well-suited for situations where data may not clearly distinguish between alternatives. In cases where the differences in data are not significant, SMART allows for equal scoring of alternatives within a smaller range, ensuring that uncertainty or low-confidence differences do not unduly influence the decision-making process. This flexibility makes SMART a practical tool for ensuring a balanced and transparent assessment of various nuclear technology options.

Among the SMRs evaluated, which include BWRX-300, HTR-PM, NuScale, RITM-200N, and SMART, the BWRX-300 stands out as the most suitable option for the Philippines based on the RTA overall score. It achieved the highest scores in KE1, KE4, KE5, and KE7. The BWRX-300's modular design and flexible siting requirements, which accommodate both coastal and inland locations, make it highly adaptable to the country's diverse geographical landscape. Its multiple cooling options and compatibility with grid systems operating at 50/60 Hz further enhance its suitability. Additionally, its seismic design, capable of withstanding a Safe Shutdown

Earthquake (SSE) of 0.3 g, is well-suited to the Philippines' earthquake-prone conditions. With a load-following capability of 50-100% and a ramp rate of 0.5% per minute, it is designed to meet fluctuating energy demands. Furthermore, the BWRX-300’s facility layout and site characteristics are optimized for safeguards, incorporating specific design requirements to enhance security and protection.

The BWRX-300 is the reactor with the greatest declared commercial sophistication. The first operational plants are expected in Canada by 2028 and Poland by 2029 (KPMG International, 2023), with estimated construction costs of USD 4,333/kW (PricewaterhouseCoopers LLP, 2021).

Monte Carlo simulation results revealed that variations in the KE1 value significantly influence the overall score of the BWRX-300 within the RTA methodology. By modeling these variations across each Key Element (KE), decision-makers gain a deeper understanding of how uncertainties and minor fluctuations in critical input factors, such as site and environmental parameters, impact the final assessment. This enhanced insight allows for more informed evaluations, ensuring that potential vulnerabilities are identified and addressed effectively to strengthen the robustness and reliability of the scoring process.

When evaluating Small Modular Reactors (SMRs), biases in vendor-supplied information in the ARIS database and data availability can pose problems. These biases can include incomplete, out-of-date, or overly optimistic data regarding a reactor's cost, safety, or efficiency, which can skew decision-making by underestimating operational challenges or ignoring risks. Conducting thorough risk assessments, involving stakeholders from a range of viewpoints, and testing pilot projects can further reduce biases and data gaps. These strategies encourage objective decision-making and increase the credibility of SMR evaluations. To address these issues, measures such as independent validation by third-party experts, transparent reporting, peer reviews, and standardized data collection can help ensure more accurate assessments.

This comprehensive approach ensures that the Philippines is well-positioned to meet its energy needs addressing the country's environmental challenges and economic needs.

XI. RECOMMENDATION AND CONCLUSION

The Philippines' exploration of Small Modular Reactors (SMRs) as part of its clean energy transition underscores its commitment to achieving energy security, affordability, and sustainability. SMRs represent a new generation of nuclear reactors defined by their "small" and "modular" characteristics. With power outputs typically capped at 300 MWe, these reactors feature components that are factory-fabricated and transportable to installation sites, allowing for scalability and reduced spatial footprints. SMRs offer significant advantages, including advanced passive safety systems, reduced emergency planning zones, and the ability to operate in remote or isolated regions. Compared to traditional nuclear power plants, SMRs are designed to shut down and cool independently without requiring operator intervention or external power, making them resilient even during extreme conditions such as earthquakes.

In comparing SMRs to renewable energy sources, key distinctions emerge. While renewables like solar and wind are critical components of a low-carbon energy future, their intermittent nature due to weather variability and diurnal cycles presents challenges to grid stability. Additionally, large-scale renewable projects often require significant land use, potentially disrupting ecosystems or displacing communities. SMRs, in contrast, provide reliable, compact, and transportable energy solutions with minimal environmental footprints. Their ability to complement renewable energy by offering consistent baseload power ensures greater grid reliability and energy security, particularly in densely populated or industrial areas with high energy demands. Furthermore, hybrid systems combining SMRs and renewables can enhance grid resilience, maximizing the strengths of both technologies.

The resilience of SMRs to seismic events is a critical factor for the Philippines, given its geographic location in the Pacific Ring of Fire, which is prone to earthquakes. Modern SMR designs incorporate robust seismic resistance measures. For instance, the BWRX-300, identified as the most suitable technology in this study, is capable of withstanding a Safe Shutdown Earthquake (SSE) of 0.3 g, ensuring operational safety during seismic events. Its below-ground construction provides additional protection against external threats, including earthquakes. Other SMR options, such as SMART and NuScale, also emphasize seismic resilience through features like passive cooling systems and reinforced containment structures, further enhancing their suitability for deployment in the Philippines.

In evaluating SMR technologies for the Philippines, this study assessed five options—BWRX-300, HTR-PM, NuScale, RITM-200N, and SMART—using a methodology that assigned weights to key elements (KEs) based on national policy goals. Site and environmental factors were given the highest weight (19%), reflecting the need to minimize environmental impact and ensure geographic and climate adaptability. Nuclear island design (18%) and technology readiness (17%) followed, emphasizing the importance of stable, proven, and low-carbon energy systems. The BWRX-300 emerged as the most suitable option due to its modular design, advanced safety systems, and compatibility with the Philippines' seismic and geographic conditions. SMART closely followed, demonstrating strong performance in nuclear safety, economic viability, and design life, while HTR-PM showed promise in technology readiness and economic performance but faced limitations in seismic adaptability and long-term safety. NuScale and RITM-200N, though innovative, scored lower due to incomplete regulatory reviews and smaller outputs. The BWRX-300's comprehensive strengths across key elements, including its ability to withstand earthquakes and integrate into both coastal and inland sites, make it the most compelling candidate for deployment.

The integration of SMRs into the Philippines' energy strategy represents a crucial step toward achieving its clean energy and economic development goals. The adoption of technologies like the BWRX-300 underscores the country's commitment to innovation and sustainability. However, successful implementation will require addressing public acceptance, securing financing, and ensuring regulatory readiness. By embracing SMRs, the Philippines positions itself as a regional leader in clean and resilient energy solutions, offering a path to long-term energy security and environmental sustainability while contributing to global efforts to combat climate change.

Monte Carlo simulation results provide decision-makers with critical insights into the robustness and sensitivity of the RTA scoring process for the BWRX-300. By modeling variations in KE scores, decision-makers can better understand how uncertainties and minor changes in input factors, like site and environmental parameters, affect the overall score. This information helps identify high-sensitivity parameters, such as KE1, which can be prioritized for closer evaluation and improvement, thereby mitigating potential risks. Additionally, the range of possible outcomes generated by the simulation—spanning minimum, maximum, and likely scores—enables decision-makers to evaluate best-case, worst-case, and most likely scenarios, supporting balanced and informed choices. By quantifying uncertainties and demonstrating their impact, Monte Carlo results enhance strategic planning and build confidence in decision-making, ensuring that choices are data-driven and account for potential challenges.

For future research, I recommend requesting the technology vendors to provide a detailed and complete technical data sheet for the SMR designs. This would facilitate a more thorough and accurate evaluation process, ensuring that all relevant technical aspects are fully considered. In addition, to enhance the credibility and rigor of the RTA scoring process, it would be beneficial to form an RTA team comprised of members from the Nuclear Energy Program Implementing Agency of the Philippines (NEPIAC). This team's expertise would ensure that the evaluation is conducted with a high level of technical proficiency, aligning with national objectives and incorporating local regulatory and safety considerations.

Future research directions should include scenario analyses to address factors such as global energy price fluctuations, supply chain disruptions, and public perception. Furthermore, studies on environmental impacts, regulatory development, economic feasibility, and the integration of SMRs with renewable energy systems should be prioritized. These initiatives will help improve the accuracy and robustness of the assessment process, ultimately guiding the Philippines toward optimal nuclear energy solutions.

Given recent advancements in nuclear fusion, such as the breakthrough experiment at the Lawrence Livermore National Laboratory, future research could also explore this technology as an alternative energy source. Comparative studies on the advantages and feasibility of nuclear fission versus nuclear fusion as energy sources may provide valuable insights into the long-term energy strategy of the Philippines.

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