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Integrating Small Modular Reactors and Policy Frameworks for Sustainable Energy Security in Indonesia

Mufatdhal[1*], Imam Supriyadi[2], Rudy Laksmono[3]
Energy Security, Indonesia Defense University
Corresponding Author: Mufatdhal mufatdhalunhan@gmail.com

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ABSTRACT

This study evaluates the potential of Small Modular Reactors (SMRs) as a sustainable solution for Indonesia's energy diversification. Amid Indonesia's rising energy demands and environmental commitments, SMRs-particularly Small Modular Molten Salt Reactors (SM-MSRs)-present an alternative to conventional power sources. SMRs offer advantages like modularity, operational efficiency, and safety, making them suitable for Indonesia's geographically dispersed landscape. Using a qualitative descriptive approach, this research examines the technical, regulatory, and societal factors influencing SMR integration. Findings reveal that while SMRs show competitive Levelized Cost of Electricity (LCOE) compared to coal, challenges remain, including stringent regulatory requirements, high initial capital costs, and limited public acceptance due to nuclear safety concerns. Policy adjustments, community engagement, and collaboration with established SMR programs globally are suggested to address these issues. Additionally, SMRs' scalability and compatibility with renewables support Indonesia's goals for a resilient energy mix, potentially transforming remote energy access. This comprehensive approach underscores the viability of SMRs within Indonesia's energy transition, contributing to a cleaner, more flexible energy infrastructure

INTRODUCTION

Interest in nuclear energy within Indonesia traces back to the post-independence period in 1945, during the administration of President Soekarno, who laid the initial groundwork for nuclear energy exploration (Lusiana et al., 2023). However, it is under the recent leadership of President Joko Widodo that nuclear energy has regained momentum as part of Indonesia's strategy to meet its rapidly growing energy demands while also adhering to international commitments aimed at combating climate change (Narindra, 2022). The consideration of nuclear power is motivated by the need to diversify energy sources and reduce the country's heavy reliance on fossil fuels, which currently dominate the national energy mix (Ditjen ketenagalistrikan ESDM, 2024). Despite these motivations, constructing traditional nuclear power plants in Indonesia poses significant challenges due to the nation's vulnerability to natural disasters, particularly earthquakes and tsunamis. Indonesia's geographic and seismic profile heightens safety concerns, requiring nuclear technologies with robust safety features that can withstand such risks (Lumbanraja & Liun, 2018). In response to these challenges, Small Modular Reactors (SMRs) have emerged as a promising alternative. SMRs offer several advantages, including reduced initial capital requirements, enhanced safety mechanisms, and modular deployment options that make them well-suited for Indonesia's geographically diverse and dispersed landscape (Murakami & Anbumozhi, 2022). Given these attributes, SMRs present a feasible solution to meeting the varied and complex energy needs across Indonesia's archipelago.

Among the various SMR technologies, Small Modular Molten Salt Reactors (SM-MSRs) hold particular promise for Indonesia (Cogswell et al., 2017). SM-MSRs combine the benefits of molten salt reactors-known for their enhanced safety and thermal efficiency-with the modular characteristics of SMRs, creating a reactor design that is safe, reliable, and suitable for deployment in diverse environments (Cogswell et al., 2017). The use of molten salt as a coolant enhances safety by providing a stable medium that operates at atmospheric pressure, thus reducing the risk of explosions or leaks that are more common with water-cooled reactors (IAEA, 2021). Additionally, the modular nature of SM-MSRs offers significant logistical and economic advantages (IAEA, 2021). SM-MSRs require less space and infrastructure than traditional nuclear reactors, allowing for flexible site selection, which is essential for Indonesia's remote and isolated regions (Huda, 2021). This flexibility aligns well with Indonesia's strategic objectives of expanding its energy portfolio in a way that is both sustainable and cost-effective, making SM-MSRs an attractive option for energy diversification.

The deployment of SMRs within Indonesia's energy infrastructure offers a range of benefits beyond merely meeting immediate energy needs. By incorporating SMRs, Indonesia has the potential to enhance energy security, reduce reliance on imported fossil fuels, and contribute to sustainable development goals. In particular, SMRs could play a pivotal role in providing energy access to Indonesia's numerous islands and remote areas, many of which face limited or inconsistent access to electricity (Imani et al., 2021). The modular and scalable design of SMRs enables phased deployment, a feature that is especially valuable in areas where large-scale energy projects are economically or logistically unfeasible due to infrastructure limitations or high investment costs (Saleh, 2023). Furthermore, the deployment of SMRs would complement existing renewable energy sources by addressing the intermittency issues that often arise with solar and wind energy. By serving as a reliable baseline power source, SMRs can stabilize the energy grid and allow for a more resilient and integrated energy system (Rahmanta, 2024).

The potential for SMRs to complement renewable energy sources adds another dimension to their viability in Indonesia. Renewable energy sources, such as solar and wind, are increasingly popular but suffer from intermittency issues, leading to fluctuations in energy supply. By integrating SMRs with these renewable sources, Indonesia could develop a hybrid energy system that offers both stability and flexibility. Such a system would not only meet current electricity demands but would also be well-equipped to handle future growth, ensuring a more resilient energy grid (Murakami & Anbumozhi, 2022; Nøland, 2024). Additionally, SMRs present a viable economic option for Indonesia's energy strategy, as they require lower upfront capital investment compared to traditional large-scale nuclear reactors. This lower financial barrier makes SMRs more accessible, especially in regions where limited resources or economic constraints hinder the deployment of more extensive energy infrastructures (Murakami & Anbumozhi, 2022).

However, the adoption of SMRs in Indonesia faces several regulatory and policy-related challenges. Currently, Indonesia's regulatory framework imposes strict requirements on nuclear technology, including mandates for locally manufactured components, licensing restrictions that limit reactors to "proven technology," and a stipulation that reactors be constructed only on land-based sites (Maharani & Mellawati, 2019). These regulations, though designed to ensure safety and local economic benefit, pose significant obstacles to SMR deployment, especially given the innovative nature of SMR technologies, which often feature novel designs and require policy flexibility. To facilitate the integration of SMRs into Indonesia's energy infrastructure, supportive policies that address these regulatory barriers are essential. Establishing a robust regulatory framework that considers safety, environmental impact, and public acceptance will be crucial for the successful deployment of SMRs (Arifianto et al., 2022; Zarebski, 2023). Furthermore, actively engaging local communities and stakeholders in the planning and implementation processes is critical for ensuring that SMR projects align with regional needs and expectations, building public trust and acceptance in nuclear technology (Arifianto et al., 2022; Johari et al., 2023).

Investment in research and development is another critical factor in advancing SMR technology and addressing challenges related to fuel supply, waste management, and operational efficiency. Enhanced R&D efforts could foster technological improvements that make SMRs more efficient and viable for diverse applications within Indonesia's energy landscape. International collaboration offers additional pathways for overcoming these obstacles, providing opportunities for Indonesia to learn from countries with established SMR programs. By partnering with nations that have successfully integrated SMRs, Indonesia can gain valuable insights into best practices, policy development, and potential operational challenges (Amatullah, 2024; Rahmanta, 2024). This knowledge sharing can accelerate the adoption of SMRs, enabling Indonesia to leverage global expertise while adapting it to local conditions (Rahmanta, 2024; Saleh, 2023). With comprehensive policy support, community engagement, and international collaboration, SMRs could significantly contribute to Indonesia's vision of a flexible and resilient energy system.

The adaptability of SMRs extends beyond electricity generation, as these reactors are capable of supporting various industrial applications. Innovative designs, such as small modular lead-cooled fast reactors (SMLFR), demonstrate the ongoing advancements in reactor technology aimed at improving safety and efficiency (Kwak & Kim, 2018). These reactors are specifically designed to address key challenges in heat removal and natural circulation, which are crucial for their safe and effective operation in Indonesia's unique environment. Additionally, SMRs incorporate inherent safety features, such as the absence of large-bore piping, which significantly reduces the risk of catastrophic failures like cooling system malfunctions (Memmott et al., 2017). This combination of regulatory adaptation and technological innovation underscores the potential role of SMRs in Indonesia's future energy landscape, offering a pathway toward a more diverse and secure energy system.

Despite the clear advantages of SMRs, there are significant research gaps and challenges that must be addressed to fully realize their potential in Indonesia. The country's current energy policies remain heavily reliant on fossil fuels, with coal and oil dominating the energy mix (Rahmanta, 2024; Ruslan, 2021). Although efforts to increase the share of renewables are underway, nuclear energy plays only a minor role, highlighting the need for more comprehensive policies that can support SMR integration within the national energy infrastructure (Arifianto et al., 2022). The regulatory framework also presents considerable barriers, as it enforces strict requirements on local manufacturing, restricts licensing to proven technologies, and mandates land-based reactor sites. These constraints, coupled with the high financial costs of SMR development, emphasize the necessity for supportive financial policies and incentives to make these projects viable. Additionally, public acceptance and engagement are vital, as nuclear energy often faces skepticism; effective communication and educational campaigns will be crucial to address public concerns and foster trust in SMR technology.

This study seeks to evaluate the potential of Small Modular Reactors (SMRs) in supporting Indonesia's energy transition, identifying the necessary policy frameworks, and assessing the opportunities and challenges of SMR implementation. By addressing both the technical and regulatory challenges, this research aims to develop comprehensive strategies for integrating SMRs into Indonesia's energy landscape, contributing to a clean and sustainable energy future. The novelty of this study lies in its holistic approach to SMR adoption, focusing on the integration of nuclear technology into Indonesia's energy mix and proposing policy frameworks that facilitate a balanced and flexible energy system.

METHODS

This study employs a descriptive research design with a qualitative approach (Creswell, 2014), complemented by a literature study method to examine the potential of Small Modular Reactors (SMRs) in Indonesia's energy landscape. Data were gathered from secondary sources, including academic journals, government policy documents, industry reports, and publications focused on nuclear energy and SMRs.

Key references include reports from Indonesia's Ministry of Energy and Mineral Resources (KESDM) and the International Atomic Energy Agency (IAEA). The literature study method ensured a systematic and comprehensive collection of relevant and credible sources, forming a robust analytical foundation. This approach facilitated an in-depth exploration of the technical, regulatory, and societal factors influencing the integration of SMRs. The analysis employed a thematic approach, categorizing data into major themes such as government policy, infrastructure readiness, technical feasibility, and socio-environmental implications. This method allowed the identification of key patterns, trends, and challenges associated with SMR deployment in Indonesia. Organizing the data into these themes enabled the development of a holistic narrative that explores the interplay between policy frameworks, infrastructure capabilities, and public acceptance in shaping the feasibility of SMRs. By integrating diverse perspectives, the methodology provides a detailed evaluation of SMRs' viability and generates actionable insights to guide decision-making in Indonesia's energy transition.

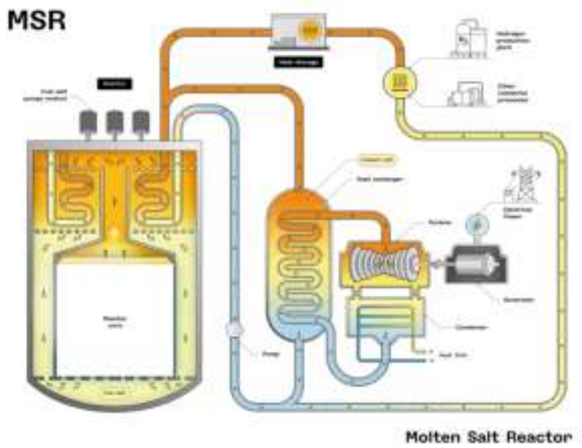
RESULTS AND DISCUSSION

Nuclear power plants offer several compelling advantages, establishing themselves as essential energy resources in meeting modern demands. Leveraging established reactor designs, nuclear energy maintains a relatively high safety profile, despite historical incidents. A notable attribute of nuclear energy is its high energy density, requiring significantly less land than other energy sources while generating minimal carbon emissions during operation, which substantially contributes to greenhouse gas reduction efforts (Athanasiou, 2024; Rahmanta, 2024). Additionally, nuclear facilities require minimal fuel storage and operate independently of weather conditions, providing a stable, uninterrupted energy supply. With high load factors, often between 80% and 90%, nuclear power is well-suited for meeting large-scale, continuous energy demands, supporting both base-load and peak demand needs (Athanasiou, 2024).

Despite these advantages, nuclear energy presents notable challenges. The supply of fissile materials, such as uranium, is concentrated in specific regions, raising concerns about supply security and geopolitical dependency. Furthermore, uranium mining and extraction pose significant environmental risks, including soil degradation, contamination, and potential harm to local ecosystems (Namekar & Nigam, 2020). Nuclear plants also require periodic refueling, and their construction often faces delays and budget overruns, frequently exceeding initial projections by over 100%. The siting of nuclear plants is limited by the need for proximity to load centers and water bodies while avoiding seismic zones, restricting viable locations (Rahmanta, 2024). Public acceptance remains a significant hurdle, driven by perceived risks of catastrophic failure in extreme events. Additionally, nuclear power requires substantial capital investment, with construction and maintenance costs often exacerbated by non-standardized designs and the need for highly specialized personnel. Managing long-term waste disposal and decommissioning adds further complexity to the sustainability and safety profile of nuclear power (Rahmanta, 2024).

Small Modular Reactors (SMRs) represent an innovative advancement in nuclear technology, specifically designed to overcome the limitations associated with traditional nuclear plants by enhancing safety, efficiency, and scalability (Hejazi et al., 2024). SMRs generally have a smaller power capacity, typically below 300 MWe, enabling a modular approach to power generation (Athanasiou, 2024). Their compact designs and passive safety features-such as gravity and natural circulation-reduce dependence on complex active systems, significantly lowering risks of mechanical failure or radioactive leaks during accidents (Hejazi et al., 2024). Additionally, the modular construction of SMRs allows core components to be factory-assembled and transported by ship or rail to the installation site. Once on-site, the modules integrate with other power system components, resulting in shorter construction times, reduced capital costs, and simplified financing options (Morales Pedraza, 2017; Murakami & Anbumozhi, 2022). Furthermore, SMRs benefit from extended refueling intervals, with some designs capable of operating for up to 30 years without refueling, enhancing their operational efficiency and reliability(Murakami & Anbumozhi, 2022).

The application potential for SMRs is considerable, extending from electricity generation for residential, commercial, and industrial sectors to providing stable energy for remote or off-grid regions. Global SMR development is progressing rapidly, with initiatives such as those by the U.S. Department of Energy aiming for commercial deployment by the mid-2030s, paving the way for broader adoption in the decades following (IAEA, 2020). A key objective of SMR deployment is to replace coal-fired plants, thereby contributing to significant reductions in greenhouse gas emissions without sacrificing energy reliability (Huda, 2021). Small Modular Molten Salt Reactors (SM-MSRs) integrate the advantages of molten salt reactor designs with modular construction, enhancing site selection flexibility, reducing operational costs, and ensuring stringent safety standards, making them an ideal choice for complex or high-safety-priority applications like those in Indonesia (Hejazi et al., 2024; Kwak & Kim, 2018)



Source: (*Molten Salt Reactors (MSR)*, n.d.)
Figure 1. Energy Conversion in a Molten Salt Reactor (MSR) System

When comparing SMR adoption in Indonesia to global contexts, specific benefits and challenges become apparent. Countries like China and the United States have advanced considerably in SMR development due to strong governmental support, efficient regulatory frameworks, and robust public-private partnerships-providing a model that Indonesia could adapt to its unique context (Namekar & Nigam, 2020). However, Indonesia faces specific regulatory and logistical challenges, including requirements for locally sourced components, strict licensing standards, and constraints related to land-based siting (Cogswell et al., 2017). These factors may limit SMR feasibility and necessitate tailored financial support frameworks and incentives to enable successful deployment.

The environmental and economic benefits of SMRs highlight their strategic value for Indonesia. By replacing fossil fuel plants, SMRs could significantly reduce greenhouse gas emissions, aligning with Indonesia’s commitments under the Paris Agreement (Arifianto et al., 2022; Muyasyaroh, 2024; Rahmanta, 2024). SMRs also offer a strategic opportunity to enhance Indonesia’s energy security, combining electricity generation with freshwater production to address both energy and water scarcity issues in remote or underserved regions (Cho et al., 2021; Huda, 2021). Moreover, the inherent safety features and innovative designs of SMRs mitigate many traditional nuclear energy risks, making them a viable option for Indonesia (Memmott et al., 2017).

To fully leverage SMRs’ potential in Indonesia, addressing both regulatory and financial obstacles is essential. The requirements for local manufacturing, proven technology, and land-based siting must be managed through supportive policies and financial incentives. Equally important is fostering public acceptance; transparent communication and community-focused education are vital to building public trust, addressing safety concerns, and ensuring social support for nuclear initiatives in Indonesia (Lumbanraja & Liun, 2018).

Government Policy on Nuclear Energy Regulation in Indonesia

Indonesia has established a comprehensive legal and regulatory framework to ensure the safe, secure, and sustainable utilization of nuclear energy. This framework comprises several pivotal regulations covering key aspects of nuclear energy activities, including energy production, safety protocols, radioactive waste management, and licensing. National Regulation No. 30/2007 on Energy identifies nuclear energy as a viable alternative within Indonesia’s energy mix, underscoring the nation’s commitment to diversifying its energy portfolio. National Regulation No. 10/1997 on Nuclear Energy serves as a foundational legal structure, defining the roles of the National Nuclear Energy Agency (BATAN), now part of the National Research and Innovation Agency (BRIN) and the Nuclear Energy Regulatory Agency (BAPETEN). BATAN (now BRIN) is primarily responsible for nuclear research, development, and the promotion of nuclear energy applications, while BAPETEN acts as an independent regulatory body overseeing the licensing, inspection, and monitoring of nuclear activities across Indonesia.

Strengthening this framework, Government Regulation No. 79/2014 on the National Energy Policy (KEN) reinforces Indonesia's commitment to expanding new and renewable energy sources, including nuclear energy, through defined targets. Government Regulation No. 54/2012 on the Safety and Security of Nuclear Installations mandates rigorous safety and security standards, ensuring that all nuclear installations are regulated to protect public health and the environment. Additionally, regulations such as Government Regulation No. 2/2014 on the Licensing of Nuclear Installations and Nuclear Utilization establish comprehensive licensing requirements, while Government Regulation No. 61/2013 on Radioactive Waste Management provides clear guidelines for the safe handling, processing, and disposal of radioactive waste, minimizing risks to the environment and public health.

Government Regulation No. 43/2006 further clarifies licensing procedures for the site selection, construction, and decommissioning of nuclear facilities. These regulations are supported by BAPETEN Chairman Decree No. 03/1999, which acts as a foundational reference for radioactive waste management. Government Regulation No. 27/2002 emphasizes that radioactive waste management practices must comply with international safety standards, particularly in areas of waste collection, processing, and storage, as mandated by the International Atomic Energy Agency (IAEA). These procedures ensure that every stage of radioactive waste handling prioritizes the safety of users and the public.

Rooted in the principles of Indonesia's 1945 Constitution, this regulatory framework-though not specifically addressing nuclear energy-promotes the peaceful use of energy for national welfare, requiring all nuclear activities to align with Indonesia’s national objectives and prioritize public and environmental safety. Together, these layers of regulation, from constitutional values to specific technical directives, ensure that nuclear energy utilization in Indonesia meets stringent safety standards, fosters operational order, and minimizes associated risks. By aligning its nuclear practices with global standards, Indonesia demonstrates its commitment to a safe, secure, and sustainable nuclear energy sector, reflecting a dedication to best practices and international safety guidelines.

Industrial Readiness for Nuclear Power Development in Indonesia

The development of an experimental power reactor in Indonesia requires a robust national industrial infrastructure, with essential contributions from sectors such as construction, mechanical, electrical, and instrumentation control to support non-nuclear components. According to assessments by the National Nuclear Energy Agency (BATAN), leading Indonesian construction companies, such as PT Hutama Karya and PT Waskita Karya, are well-prepared for this undertaking, drawing from their experience in past research reactor projects (Dewi et al., 2020). The architectural and engineering industries, represented by PT Rekayasa Industri and PT Krakatau Engineering, play crucial roles in technical design, project management, and construction procurement (Dewi et al., 2020). This involvement ensures that the project benefits from expertise in high-quality technical planning and execution.

The mechanical sector, with key players like PT Barata Indonesia and PT Siemens Indonesia, demonstrates the capacity to produce essential components, including turbines, generators, and condensers. By engaging these companies, the project not only meets its operational demands but also enhances the Domestic Content Level (TKDN), thereby reducing dependence on imports (Dewi et al., 2020). This alignment with national capabilities strengthens Indonesia’s industrial framework, positioning it for sustained support of nuclear projects.

Similarly, the electrical and instrumentation control sectors play a vital role in ensuring the readiness of primary components for the reactor. Companies such as PT ABB Sakti Industri, PT Trafoindo Perkasa, and PT Kabelindo Murni represent the national electrical industry and are capable of supplying critical components like switchgear, transformers, power cables, and electrical panels that meet international standards. In the instrumentation control sector, PT Yokogawa Indonesia and PT Maju Mapan Mandiri contribute essential items such as communication systems, temperature controllers, and reactor protection systems crucial for safe reactor operation. By adhering to rigorous international standards, these components meet the stringent requirements necessary for nuclear facilities, further boosting TKDN and enhancing Indonesia’s capacity to manage complex nuclear projects (Dewi et al., 2020).

In addition to the experimental power reactor project, the Indonesian government has endorsed the development of nuclear power plants (PLTN) using Small Modular Reactor (SMR) technology. A recommendation letter was granted to PT ThorCon Power Indonesia for the Thorium Molten Salt Reactor (TMSR500) project (*About – Thorcon Power Indonesia*, n.d.). This initiative is expected to support Indonesia’s transition to clean and sustainable energy through efficient modular reactor technology. By advancing in SMR development, Indonesia aims to strengthen its standing in safe and environmentally friendly nuclear energy production.

Evaluating the Levelized Cost of Electricity and Transition Strategies in Indonesia’s Energy Mix

In Indonesia, the Levelized Cost of Electricity (LCOE) for coal-fired power plants remains a crucial metric for evaluating electricity production costs, reflecting coal’s dominant role in the national energy mix. This metric encompasses capital, operational, and maintenance costs over a plant's lifetime, yielding a cost per kilowatt-hour. Currently, coal power is more economically viable than renewables like solar and wind, due in part to government subsidies and Indonesia’s relatively low domestic coal prices, which keep coal plants’ operational costs below the global average. However, as environmental regulations intensify and international emissions standards tighten, coal plants are incurring increased investment costs, which may impact Indonesia’s energy cost structure as it works to modernize its infrastructure (IESR, 2019).

The LCOE for coal-fired power in Indonesia varies significantly based on technology. For instance, coal mine mouth plants, located close to coal sources to minimize transportation costs, exhibit an LCOE range of approximately 7.31 to 8.41 cents per kWh. Subcritical plants, which operate with lower efficiency and higher emissions, have an LCOE of 6.11 to 8.41 cents per kWh. Advanced supercritical plants, which use higher temperatures and pressures to increase efficiency, show a slightly lower range of 5.77 to 8.38 cents per kWh, while the latest ultra-supercritical plants achieve the highest efficiency and lowest emissions, with an LCOE between 5.83 and 8.38 cents per kWh. These variations illustrate the economic and environmental trade-offs of each technology type as Indonesia seeks to balance affordable energy with sustainability (IESR, 2019).

As the global shift toward low-carbon energy accelerates, LCOE analysis becomes increasingly important for Indonesian policymakers assessing the competitiveness of coal relative to renewables. Factors such as capital expenditure (CAPEX), operational expenses (OPEX), and the weighted average cost of capital (WACC) have a strong influence on coal's LCOE, while renewables are more sensitive to CAPEX and capacity factors. Strategic policies, such as CAPEX incentives for renewables or mechanisms to lower WACC, could enhance the competitiveness of renewable energy, supporting Indonesia's goal of achieving a 23% renewable energy share by 2025 and promoting a more sustainable national energy policy.

In addition to renewables, Small Modular Reactors (SMRs) present a promising pathway for Indonesia to diversify its energy portfolio with low-carbon options. Techno-economic analyses of various SMR designs such as Light-Water SMRs (LW-SMRs), Gas-Cooled SMRs (GC-SMRs), and Molten Salt SMRs (MS-SMRs) indicate competitive LCOE values. LW-SMRs have an estimated LCOE of around 8.96 cents per kWh, while GC-SMRs and MS-SMRs are slightly more cost-effective, with LCOEs of approximately 8.15 and 8.06 cents per kWh, respectively (Asuega et al., 2023). Although the LCOE of SMRs is currently higher than that of advanced coal technologies, their modularization, lower emissions, and resilience to environmental regulations make them a viable alternative, especially as Indonesia seeks flexible, scalable, and sustainable energy solutions.

According to the 2023 Electricity Statistics Report, Indonesia's energy mix is dominated by coal-fired power plants (PLTU), which comprise 54.58% (49,725 MW) of the total installed capacity, followed by gas-fired plants (PLTG) at 25.46% (23,200 MW), diesel plants (PLTD) at 5.09% (4,641 MW), and renewables at 14.88% (13,565 MW), totaling 91,131 MW of generation capacity. To align with its cleaner energy commitments and strengthen national energy resilience, as mandated by Government Regulation No. 79 of 2014, Indonesia aims to reduce the share of coal-fired power by 8.12% (equivalent to 7,395 MW).

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	ThorCon International, first deployment in Indonesia
Reactor type	Thermal molten salt reactor
Coolant/moderator	Molten salts / graphite
Thermal/electrical capacity, MW(t)/MW(e)	557 / 250 (per module)
Primary circulation	Forced (4 pumps), 1 per loop
System operating pressures (4 loops: fuel salt, clean salt, solar salt, steam), MPa	0.6 / 2.9 / 0.86 /25.7
Core Inlet/Outlet fuel-salt temperature (°C)	565 / 704
Fuel type/assembly array	UF_4, ThF_4 / n/a.
Number of fuel assemblies	1 (one mixture of fuel salt)
Fuel enrichment (%)	5.0 minimum / 19.7 maximum
Discharge burnup (GWd/ton)	12.4
Refuelling cycle (months)	48
Reactivity control mechanism	Negative temp coeff, salt flow rate; fissile/fertile additions
Approach to safety systems	Intrinsic, passive, using natural circulation, water
Design life (years)	80
Plant footprint (m^2)	67x174
Can height/diameter (m)	10.3 / 7.8
Can weight (metric ton)	343
Seismic design (SSE)	1.0 (under review)
Fuel cycle requirements / approach	Thorium converter. Fissile LEU05, LEU19, or plutonium
Distinguishing features	Full passive safety, short construction time
Design status	Complete basic design

Source: *(IAEA, 2020)*
Figure 2. Molten Salt SMR

This capacity could be replaced with approximately 30 units of 250 MW SMRs, such as TMSR-type reactors, each with a thermal capacity of 500 MWth and an electrical output of 250 MWe. This shift would adjust Indonesia's energy mix to 46.45% for coal, maintain current shares for gas and diesel, and increase renewables to 23%, moving the nation toward a more balanced and sustainable energy portfolio.

Social and Environmental Challenges in Indonesia's Nuclear Energy Development

The development of nuclear power plants (NPPs) in Indonesia faces substantial social and environmental challenges. While NPPs offer a sustainable and reliable source of clean energy to meet Indonesia's growing energy demands, public concerns about the risks of nuclear accidents remain high. Historical events like Chernobyl and Fukushima have contributed to a persistent stigma surrounding nuclear energy, with many perceiving NPPs as inherently dangerous (Huda, 2021; Lusiana et al., 2023).

Concerns over radiation exposure and potential environmental impacts have fueled a "Not In My Backyard" (NIMBY) sentiment in areas proposed as potential NPP sites, including Muria and Bangka Belitung. Communities in these regions generally oppose the establishment of nearby nuclear facilities, despite the rising demand for sustainable energy (Huda, 2021).

This resistance is largely due to limited public understanding of nuclear technology's safety measures and its benefits. Misconceptions about the risks and benefits of NPPs have reinforced negative perceptions, often overlooking nuclear energy's potential role in strengthening national energy security (Lusiana et al., 2023). A structured approach to public outreach and education is therefore essential to address these misunderstandings and improve nuclear literacy.
Intensified public outreach and education are critical to providing balanced information on both the benefits and risks of NPPs. By fostering a deeper understanding, public receptiveness to NPPs as a viable solution to energy challenges may improve, potentially reducing the social resistance that has historically hindered their development (Huda, 2021).

Furthermore, active involvement of local communities should be prioritized throughout each phase of NPP planning and development. Such engagement enables communities to better understand national energy policy goals and the environmental implications of NPPs at the local level, which can enhance public acceptance. Transparent communication and public diplomacy are also crucial for alleviating public concerns. This approach is expected to mitigate misunderstandings regarding NPP risks and foster a more informed, balanced perspective.

CONCLUSION

This study underscores the transformative potential of Small Modular Reactors (SMRs), particularly Small Modular Molten Salt Reactors (SM-MSRs), to diversify Indonesia's energy landscape, enhance energy security, and reduce reliance on fossil fuels. With modular deployment advantages, operational efficiency, and inherent safety features, SMRs align well with Indonesia's commitments to the Paris Agreement. The phased deployment capacity of SMRs makes them particularly suitable for remote and infrastructure-limited regions, supporting sustainable and widespread energy access across Indonesia.

As a low-carbon alternative, SMRs offer competitive Levelized Cost of Electricity (LCOE) rates compared to advanced coal technologies, addressing climate goals while serving remote areas unsuitable for large-scale plants. However, public apprehension surrounding nuclear safety persists, rooted in historical nuclear incidents. While SMRs' advanced safety features mitigate some risks, transparent communication and robust public education initiatives are critical to building public trust. Additionally, effective management of environmental concerns, such as uranium mining and waste handling, is essential to ensure SMRs contribute positively to Indonesia's sustainability targets.

Regulatory and infrastructural challenges add further complexity to SMR deployment. Indonesia's current regulatory framework mandates strict licensing, emphasizes local component manufacturing, and restricts reactor siting to land-based locations, potentially limiting SMR flexibility. Moreover, enhancing domestic industrial capabilities-particularly in component production and assembly-is crucial for fostering a reliable SMR supply chain. Developing local expertise and reducing import dependency will support a more self-sustaining nuclear infrastructure, promoting long-term energy independence.

To maximize the potential of SMRs in Indonesia, several strategic actions are recommended. First, revising regulatory frameworks to support SMR innovation and adaptability is essential. This includes policies that incentivize local industry involvement through financial support and R&D initiatives, fostering smoother integration. Launching a pilot SMR project would provide Indonesia with valuable insights, facilitating broader implementation. Lastly, prioritizing long-term waste management strategies will help address environmental concerns, ensuring that SMRs are sustainably aligned with Indonesia's goals for a cleaner, resilient energy future.

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