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(Research) Article

Integrated Techno-Economic Evaluation, Monte Carlo Probabilistic Reliability, Unit Commitment Optimization, and Frequency Stability of Small Modular Reactor (SMR) Integration in Isolated Systems of 300–1000 MW

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Abstract: Electric power systems in island regions often operate as isolated grids, heavily dependent on diesel generators, leading to high fuel costs and vulnerability to fluctuations in global energy prices. This study presents an integrated evaluation framework for analyzing the integration of Small Modular Reactors (SMRs) into these isolated power systems. The research combines techno-economic analysis using Levelized Cost of Electricity (LCOE), probabilistic reliability simulation through Sequential Monte Carlo Simulation, operational optimization with the Unit Commitment model, and system frequency stability analysis. A case study was conducted on an island grid system with a peak load of 650 MW. The simulation results show that integrating SMRs can reduce Expected Energy Not Served (EENS) by over 60% and yield a median LCOE of approximately 77 USD/MWh. These results suggest that SMRs offer a reliable, cost-effective generation solution for isolated grids, improving both energy security and economic efficiency by reducing reliance on diesel and enhancing the sustainability of energy systems in remote areas.

Keywords: Isolated Grid; Monte Carlo Simulation; Reliability Analysis; Small Modular Reactor; Unit Commitment.

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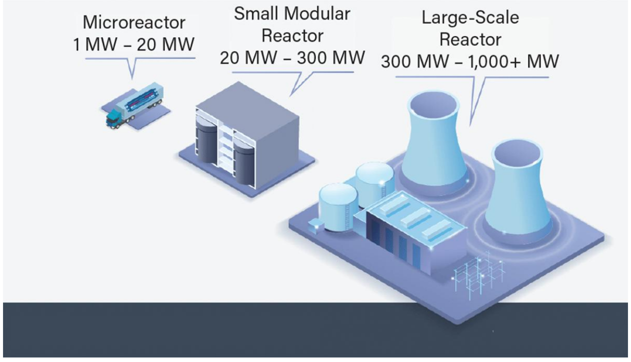
1. Introduction

Isolated power systems are often found in island regions and remote areas not connected to the main transmission grid. These systems generally rely on diesel generators due to their operational flexibility and ease of installation. However, diesel generators have high fuel costs and increase carbon emissions.

Small Modular Reactors (SMRs) are a new generation of nuclear power generation technology designed with smaller capacities than conventional nuclear power plants. The modular design allows for phased construction, increased safety, and flexible integration into medium-scale power systems.



Picture 1. Power Reactor comparison

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Indonesia is one of the countries making significant progress in the development and implementation of nuclear power. This is evidenced by the formation of a preparatory team for the establishment of the Nuclear Energy Program Implementation Organization (NEPIO) [2]. In addition to the formation of the NEPIO preparatory team, further progress is evident in the increasing interest of developers to invest in the construction of nuclear power plants in Indonesia.

Developers such as PT. Thorcon Power Indonesia with its Thorium Molten Salt Reactor (TMSR)[3] and NuScale Power, LLC with its NuScale reactor are planning to invest in the construction of an SMR-type nuclear power plant at the site, which will ultimately be approved by the Indonesian government..

2. Preliminaries

Previous research has shown that SMRs have the potential to improve energy resilience in remote power systems. Power system reliability analysis is typically conducted using probabilistic methods such as Monte Carlo Simulation, which can model the uncertainty of generating unit failures.

A literature study on the design and technology of the CAREM-25 type small modular reactor (SMR) conducted by Ery Diniardi, Anwar Ilmar Ramadhan, and Hasan Basri (2013). New and renewable energy is currently a necessary energy source to overcome electricity shortages for both households and industry. To overcome this energy shortage, in accordance with Presidential Regulation No. 5 of 2006 concerning national energy policy, the aim is to increase the diversification of energy sources beyond fossil fuels. This research method was carried out through a literature review, by examining the CAREM-25 reactor system and technology [3]. This resulted in a comprehensive assessment of the CAREM design and the thermohydraulic aspects of the reactor, which already has a passive cooling system and natural circulation.

In 2022, P2STPIBN continued its safety study on the implications of multi-module designs applied to SMR-type reactors. This study was chosen due to the development of SMR nuclear power plant technology, which adopts a multi-module design, so that the reactor unit for a nuclear power plant consists of several uniform modules located in a single, adjacent location. Furthermore, these reactors have a compact configuration with shared structures, systems, and components (SSK) across multiple modules. This naturally results in several safety implications, which require understanding and identification.

3. Proposed Method

This research methodology combines four main approaches:

a) Techno-economic evaluation using LCOE
b) Reliability simulation using Sequential Monte Carlo Simulation
c) Plant operation optimization using the Unit Commitment model, and
d) Frequency stability analysis using a power system dynamics model

The economic evaluation was conducted using the Levelized Cost of Electricity (LCOE) approach based on discounted cash flow.

$$LCOE = \frac{\sum_{t=0}^{N} \frac{I_t+O_t+F_t+D_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}}$$

where:
It = capital expenditure in year t
Ot = operation and maintenance costs
Ft_ = fuel costs
Dt = decommissioning costs
r = discount rate
Et = electrical energy generated

Adequacy evaluation uses the Capacity Outage Probability Table (COPT). Each combination of generating unit outages produces a probability of available capacity, Ck. Loss of Load Probability is calculated as

$$LOLP = \sum Pr(C_k < L)$$

Then, Expected Energy Not Served calculate as:

$$EENS = \sum (L - C_k)^{+} \cdot Pr(C_k) \cdot \Delta t$$

where
L = peak load
(x)+=max(0,x)(x)^+ = \max(0,x)(x)+=max(0,x)
Δt (Delta t)= time interval
The main parameters analyzed include:
a. Forced Outage Rate (FOR) of each unit
b. System reserve margin
c. Largest unit size (N-1 contingency)

Frequency stability analysis is performed using the swing equation of the equivalent system:

$$2H_{sys}\frac{d\Delta f}{dt} = \frac{\Delta P_m - \Delta P_e}{S_{base}}$$

Hsys {sys} = total system inertia
ΔP (Delta P) = power loss due to contingency
Sbase S{base} = system capacity

The initial RoCoF can be approximated as

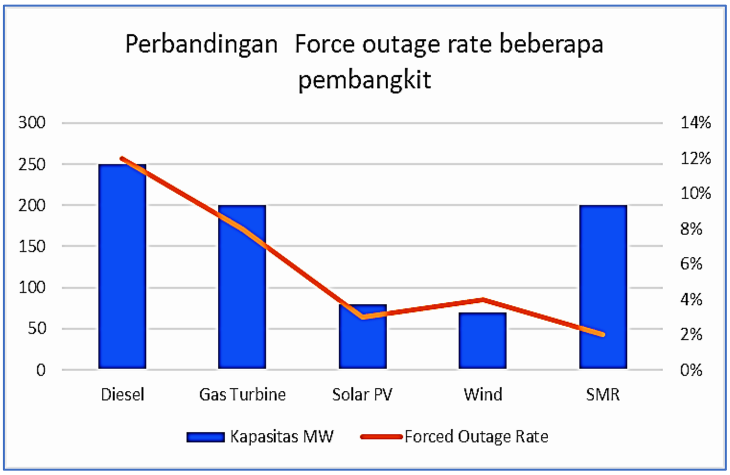
$$RoCoF = \frac{\Delta P}{2H_{sys}S_{base}}$$

The nadir frequency is determined based on the balance between power loss and primary response (governor response). The operational limits used refer to common practice standards for small systems:
a. RoCoF < 1 Hz/s
b. Frequency nadir > 49 Hz (sistem 50 Hz)

As a test material in this study, an SMR system was used with the characteristics as stated in table 1.

. **Table 1.** SMR system specification

Parameter Sistem	Nilai
Peak Load	**650 MW**
Minimum Load	**320 MW**
Reserve Margin	**30%**
Discount Rate	**8%**
Planning Horizon	**30 tahun**



Picture 2. Forced outage

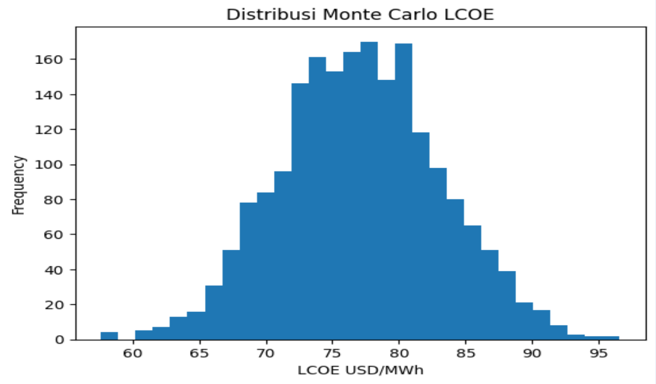
From the table data, it can be seen that the comparison of the outage rate with the power capacity of the SMR generator is the smallest so that it has a large potential value that can be developed further.

4. Results and Discussion

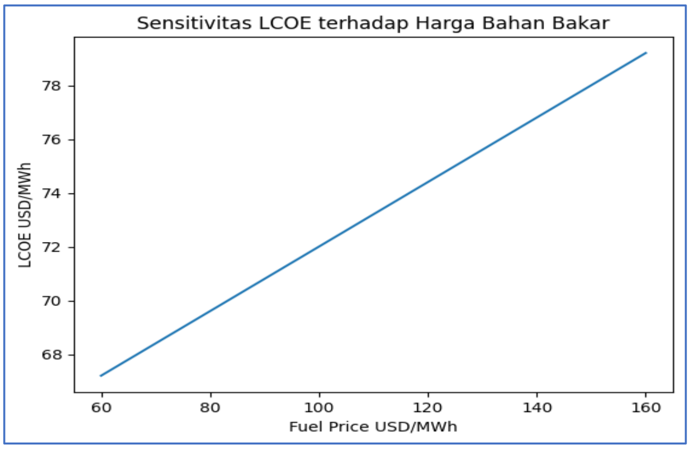
Based on the results of processing primary data obtained using the methodology discussed, the results can be analyzed and categorized into the following categories:

4.1. LCOE Impact

SMR integration demonstrates relatively stable energy costs relative to fuel price fluctuations, in contrast to gas plants, which have a predominantly variable cost component. In high gas price scenarios, SMRs become competitive, even lower than CCGT plants.



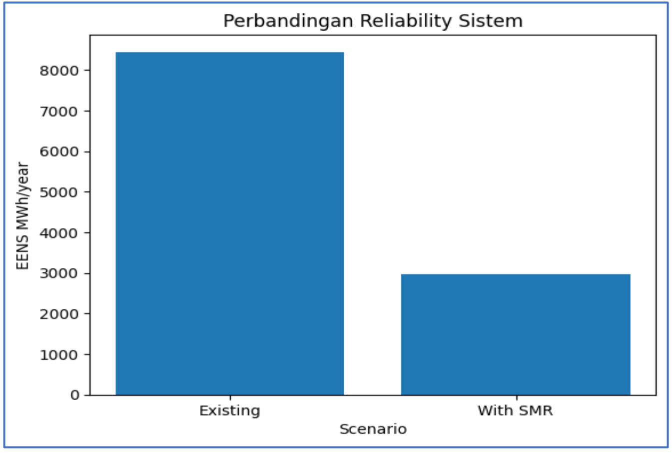
Picture 3. LCOE Monte Carlo Distribution



Picture 4. Sensitifitas LCOE with fuel

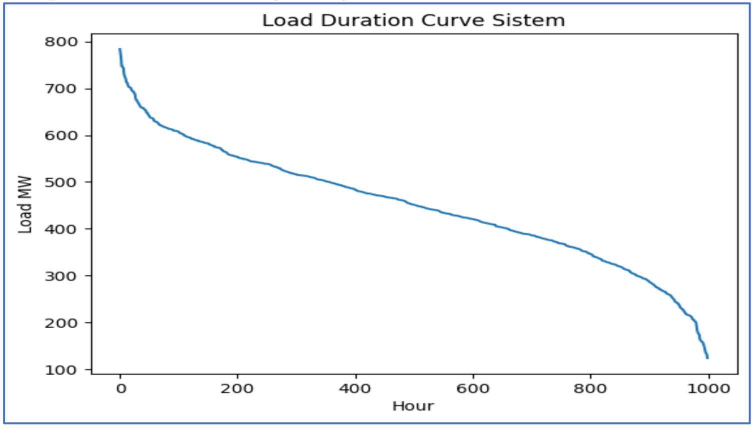
4.2 Adequacy Impact

The addition of SMR increases the system's firm capacity. With a lower FOR compared to conventional thermal units, the EENS value decreases significantly



Picture 5. Reabiltas system comparison

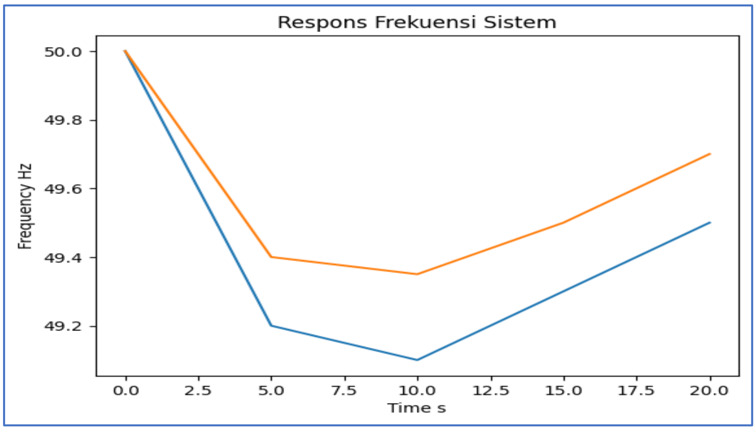
However, if the SMR unit capacity is too large relative to the total system, the probability of load loss during an outage may increase. Therefore, a modular multi-unit configuration is preferred over a single large unit.



Picture 6. Load duration system

4.3. Frequency Stability Impact

Regarding the size of an SMR unit is significant to the total system capacity, the loss of a single unit can result in a high RoCoF. In low-inertia systems, the RoCoF value can exceed the under-frequency relay protection limits



Picture 7. Respon Frequency system

5. Conclusions

This research develops an integrated evaluation framework to assess the integration of SMRs in isolated grid systems at the 300–1000 MW scale.

Key findings:

a. SMRs increase firm capacity and reduce EENS.
b. SMRs reduce cost sensitivity to fuel price volatility.
c. Inertia management and primary response are key factors for successful integration.

Further developments include:

a. Time-series-based chronological unit commitment simulation
b. BESS integration for fast frequency response
c. Monte Carlo-based probabilistic analysis.

This framework can serve as an initial reference for planning isolated grid electricity systems based on modular nuclear technology in Indonesia.

Simulation results show that SMR integration significantly improves power system reliability. The reduction in the EENS value indicates increased generating capacity adequacy and a reduced risk of power outages in isolated grid systems.

This research demonstrates that integrating Small Modular Reactors into isolated power systems can improve system reliability and generate competitive electricity costs. The evaluation framework provides a comprehensive approach for future power system planning..

Author Contributions: In this study, the first author obtained and processed primary data obtained from the Energy and Mineral Resources Management Agency. This data was combined with the modular reactor management method. The second author researched and sought alternatives that best suited Indonesia's electrical power needs. Data processing was carried out with the help of LCEO Monte Carlo software for validation and as a consideration in data analysis. Administration and funding were carried out independently by the first and second authors.

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Conflicts of Interest: The authors declare no conflict of interest that might be perceived as inappropriately influencing the representation or interpretation of the reported results. In the design of the study, in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish, the ideas and thoughts of the authors are solely those of the authors and no other party was involved in the decision to publish the results.

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