Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/AN15.20250362
Published: February 18, 2025

Techno-economic Assessment and Risk Considerations of Thorium-Based Molten Salt Reactor Nuclear Power Plants for Indonesia's Energy Future

Randy Akmalsyah[1*], **Armand Omar Moeis**[2]
Department of Industrial Engineering
Faculty of Engineering, University of Indonesia
Indonesia
[1]akmalsyah.randy@gmail.com, [2]armand.omar@ui.ac.id

Eddie Widiono
Founder, Indonesia Smart Grid Initiative (PJCI)
Jakarta
ewatsuka@gmail.com

Abstract

This study evaluates the investment feasibility of Molten Salt Reactor (MSR) technology for Nuclear Power Plants (NPPs) in Bangka Belitung through the Value at Risk (VaR) method. It examines the economic viability of MSR-based NPPs and identifies critical risks affecting investment parameters. The analysis integrates primary and secondary data, employing a discounted cash flow financial model and Monte Carlo simulations with 10,000 iterations at a 95% confidence level. The findings indicate that MSR NPPs are economically viable, with a project Net Present Value (NPV) of $338.7 million, an Internal Rate of Return (IRR) of 13.06%, a Profitability Index (PI) of 1.40, and a Discounted Payback Period (DPP) of 11.19 years. Key risks identified include extended construction timelines, public perception issues, fuel supply disruptions, policy changes, and thermal efficiency reductions. The VaR analysis using Monte Carlo simulations further highlights the potential for significant investment losses if these risks materialize, particularly impacting critical financial factors such as Power Purchase Agreements (PPA) and Overnight Construction Costs (OCC). This research provides valuable insights into advancing nuclear energy development in Indonesia, supporting the nation's energy demand growth and resilience.

Keywords
Economic Analysis, Thorium, Nuclear Power Plant, Value at Risk, Monte Carlo

1. Introduction

Indonesia's energy demand is growing rapidly, driven by industrial expansion, urbanization, and population growth. Electricity demand is projected to increase by 4.9% annually, highlighting the critical need for a reliable and efficient energy supply (PT PLN [Persero], 2021). Currently, Indonesia's energy mix is heavily reliant on fossil fuels, with new and renewable energy contributing only 12.3% as of 2022, falling short of government targets (METIIRES, 2023; Ministry of Energy and Mineral Resources [ESDM], 2022).

Nuclear energy has been proposed as a potential solution to address Indonesia's growing energy demand while diversifying its energy portfolio (Kanugrahan & Hakam, 2023). Despite several plans, Indonesia has yet to establish a nuclear power plant (NPP), and nuclear energy remains absent from its current energy mix (Permana, Trianti, & Rahmansyah, 2023). Advocates of nuclear power cite its benefits, including low operational costs, efficient land use, stable energy output, and minimal workplace accidents (IEA, 2022). However, challenges such as long construction timelines, radioactive waste management, and public perception continue to hinder its adoption (Locatelli et al., 2013).

Recent advancements in nuclear technology, particularly Generation IV reactors, aim to overcome these challenges. Six designs are under development: Very High-Temperature Reactor (VHTR), Supercritical Water Reactor (SCWR), Molten Salt Reactor (MSR), Sodium-Cooled Fast Reactor (SFR), Lead-Cooled Fast Reactor (LFR), and Gas-Cooled Fast Reactor (GFR) (Energy Education, 2023). These designs promise enhanced safety, efficiency, and sustainability, with the MSR gaining attention for its use of thorium as a fuel source.

Indonesia's substantial thorium reserves, particularly in the Bangka Belitung region, further strengthen the case for MSR technology. Thorium, often a by-product of tin mining, generates radioactive waste with shorter half-lives compared to uranium, making it an attractive option for reducing long-term waste management challenges (World Nuclear Association, 2023). In line with this, PT Thorcon Power Indonesia has proposed the development of an MSR-based NPP as an independent power producer (IPP) (PT Thorcon Power Indonesia, 2021).

1.1 Objectives

The objective of this study is to evaluate the investment feasibility of implementing a Molten Salt Reactor (MSR) technology-based Nuclear Power Plant (NPP) in Bangka Belitung, Indonesia, using the Value at Risk (VaR) methodology. Specifically, this research aims to assess the economic viability of the MSR NPP, identify and quantify the potential risks affecting investment parameters, and analyze their impact on feasibility. Through a detailed discounted cash flow financial model and Monte Carlo simulations, this study seeks to provide valuable insights into the techno-economic prospects of deploying MSR technology to support Indonesia's energy demand and resilience.

2. Literature Review

2.1 Nuclear Energy

Nuclear energy is a form of thermal energy produced through reactions within atomic nuclei, specifically via fission (splitting large atoms like uranium-235) or fusion (combining light atoms like hydrogen isotopes). This process releases substantial energy, which is used to produce steam that drives turbines to generate electricity. Since it does not involve burning fossil fuels, nuclear energy is considered a low-carbon energy source, making it a crucial tool in mitigating climate change (Brook, 2012).

Generation IV reactors represent a significant leap in nuclear technology, designed to overcome the limitations of earlier generations. These reactors prioritize efficiency, safety, sustainability, and the reduction of radioactive waste. Utilizing innovative designs, advanced fuels, and more effective cooling systems, they produce energy with lower environmental and operational risks (Knapp and Pevec, 2018). A notable advantage of Generation IV reactors is their ability to use nuclear fuel more efficiently, including thorium or plutonium from nuclear waste. Additionally, they feature passive safety mechanisms that allow automatic stabilization during emergencies without human intervention. These attributes position Generation IV reactors as a pivotal technology in achieving global net-zero carbon emission targets.

Fission, the core process in nuclear power generation, involves splitting heavy atomic nuclei (e.g., uranium or plutonium) into smaller ones, releasing significant heat and additional neutrons. This chain reaction sustains the energy production necessary for electricity generation. In MSRs, fission occurs in a medium of molten salt, which serves as both the fuel and coolant. This setup operates efficiently at high temperatures without reaching boiling points, enabling superior thermal efficiency compared to conventional reactors. The molten salt also captures byproducts of the fission process, enhancing operational safety. MSRs are designed to utilize thorium as a fuel source, converting it into uranium-233 through a stable chain reaction within the molten salt (Gill et al., 2014). This innovative design supports the production of clean, efficient, and sustainable energy.

Thorium, a naturally occurring radioactive element, offers a cleaner and safer alternative to uranium as a nuclear fuel. Abundant in the Earth's crust, particularly in minerals like monazite, thorium is more economical and sustainable for power generation. While not inherently fissile, thorium can be converted into uranium-233 through neutron bombardment, which then serves as a viable nuclear fuel. Thorium-based reactors, such as MSRs, generate less longlived radioactive waste, easing waste management challenges (Englert et al., 2012). With its potential to support clean and sustainable energy, thorium is regarded as a groundbreaking solution for meeting future energy demands.

2.2 Discounted Cash Flow Model

Financial models are essential tools for evaluating investment decisions by analyzing key aspects such as revenue, costs, profits, cash flow, and business value. A deep understanding of an asset's value and the factors influencing it is critical for informed investment decisions (Damodaran, 2006). Among the primary valuation methods, the Discounted Cash Flow (DCF) approach estimates the present value of future cash flows, Relative Valuation compares similar assets, and Contingent Claim Valuation applies option-pricing models.

These models are widely employed in strategic planning, investment feasibility studies, and fundraising. They also allow for sensitivity analysis to assess the impact of varying assumptions on financial outcomes. By quantifying potential returns and risks, financial models enable data-driven decision-making for managers, entrepreneurs, analysts, and investors.

The DCF model evaluates investment feasibility by calculating the present value of future cash flows using a discount rate that reflects risk and the cost of capital. Two main approaches guide this calculation (Rothwell, 2015):

- Invested Capital Logic: Focuses on cash flows available to all capital providers (equity and debt holders).
- Shareholder Capital Logic: Considers cash flows available only to equity holders.

The Free Cash Flow to Firm (FCFF) is central to the *invested capital logic*. It represents net cash flow (NCF) available to both debt and equity holders and is calculated as follows:

$$\begin{gathered} FCFF = EBIT - Tax\ on\ EBIT + Depreciation\ \&\ Amortization \\ +\Delta\ Net\ Working\ Capital + \Delta Capital\ Expanditure \end{gathered} \tag{1}$$

The discount rate for FCFF is the Weighted Average Cost of Capital (WACC), which accounts for the expected return on equity and the after-tax cost of debt using following formula:

$$WACC = \frac{D}{D+E} \times k_D \times (1 - t_c) + \frac{E}{D+E} \times k_e \tag{2}$$

The formula represents the Weighted Average Cost of Capital (WACC), which calculates a company's overall cost of financing by combining the after-tax cost of debt ($k_D \times (1 - t_c)$) and the cost of equity (k_e), weighted by their respective proportions in the capital structure. The weights, $\frac{D}{D+E}$ for debt and $\frac{E}{D+E}$ for equity, reflect the relative contribution of each component to the total financing, ensuring that the cost of capital accurately captures the funding mix. Here, D represents the market value of debt, E is the market value of equity, k_D is the cost of debt (such as interest rates), t_c is the corporate tax rate (accounting for the tax-deductible nature of interest payments), and k_e is the cost of equity, which is the return required by equity investors. This formula is essential for assessing the minimum return a company must achieve on its investments to satisfy both debt and equity holders.

Investment decisions rely on methods that account for the time value of money, primarily (Neely, 2015):

1. Net Present Value (NPV): Measures the absolute value added by the investment
2. Profitability Index (PI): Evaluates the relative profitability of the investment.
3. Internal Rate of Return (IRR): Determines the discount rate at which NPV equals zero.
4. Discounted Payback Period (DPP): Estimates the time required to recover the initial investment.

These methods, collectively known as discounted cash flow (DCF) techniques, are preferred over non-DCF approaches like Return on Investment (ROI), as they incorporate the time value of money, providing a more accurate representation of an investment's financial performance.

2.3 Value at Risk

Value at Risk (VaR) is a widely used method to quantify financial risk by estimating the maximum potential loss of an asset, portfolio, or investment over a specific time frame and at a given confidence level. It provides a clear, numerical insight into the potential downside under unfavorable market conditions. For instance, a VaR of 500 million at a 95% confidence level over one year implies a 5% probability that losses will exceed 500 million within that year (Jorion, 2007).

Three primary approaches are used to calculate VaR:

1. Historical Method: Relies on historical market data to estimate potential losses based on past performance.
2. Variance-Covariance Method: Assumes returns are normally distributed and uses statistical measures like mean and standard deviation to calculate risk.
3. Monte Carlo Simulation: Employs computational techniques to simulate numerous scenarios, generating risk estimates based on input parameters and random variables (Hull, 2018).

2.4 Monte Carlo Simulation

Monte Carlo simulation is a widely used computational technique for modeling and analyzing the impact of uncertainty in various systems. Originating in the 1940s during the Manhattan Project, it employs random sampling and statistical modeling to estimate the outcomes of processes with inherent uncertainty (Metropolis & Ulam, 1949). This method is particularly valuable in financial analysis, engineering, and risk management due to its ability to incorporate probabilistic inputs and generate a range of possible outcomes (Glasserman, 2004). In financial modeling, Monte Carlo simulation helps assess project feasibility by providing insight into the variability of key performance indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR) (Boyle, 1977). Additionally, it is instrumental in risk analysis by quantifying the Value at Risk (VaR) and other risk measures under uncertain conditions (Jorion, 2007). With advancements in computational power, Monte Carlo simulation has become even more accessible and efficient for analyzing complex, multi-variable systems.

2.5 Levelized Cost of Electricity (LCOE)

Levelized Cost of Electricity (LCOE) represents the average cost required to produce electricity from a power generation asset over its lifetime. It serves as a tool to compare the costs of different energy sources, aiding decision-makers in evaluating the feasibility and competitiveness of power generation projects. By using LCOE, various types of power plants can be compared, even if they have different cost components, such as initial investment, operational expenses, and maintenance costs (Rothwell, 2015).

$$LCOE = \frac{\sum_t (Investment_t + \ O\&M_t + Fuel_t) \cdot (1+r)^{-t}}{\sum_t (Electricity_t) \cdot (1+r)^{-t}} \tag{3}$$

The LCOE formula calculates the average cost of electricity over a project's lifetime by dividing the total discounted costs—investment, O&M, and fuel—by the total discounted electricity output. The discount factor, $(1+r)^{-t}$, accounts for the time value of money, making LCOE a key metric for evaluating the cost-effectiveness and financial feasibility of energy projects.

3. Methods

This study evaluates the investment feasibility of a Molten Salt Reactor (MSR)-based Nuclear Power Plant (NPP) in Bangka Belitung using the Value at Risk (VaR) method. The methodology involves developing a Discounted Cash Flow (DCF) financial model to calculate key investment metrics, such as Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI), Discounted Payback Period (DPP) and Levelized Cost of Electricity (LCOE). These metrics provide a baseline for the project's economic viability. To account for uncertainties, Monte Carlo simulations are conducted with 10,000 iterations at a 95% confidence level, ensuring robust risk analysis and accurate scenario modeling.

4. Data Collection

The Overnight Construction Cost (OCC) of $1490/kW and the Maximum Rated Power (P) of 500,000 kW were sourced from Thorcon Indonesia. The Interest During Construction (IDC) of 13.88% was calculated using the method in Geoffrey Rothwell's *The Economics of Future Nuclear Power*, where IDC is a percentage markup on OCC, reflecting time-dependent construction costs. Table 1 shows the Nth-of-a-kind 2024 Thorcon's total construction cost.

Table 1. Investment Cost

Components	Value	Source
Overnight Construction Cost (OCC)	$1490/kW	Thorcon
interest during construction (IDC)	13.88%	Calculation
Total Construction Cost, *Kc* ($/kW)	1694.4	Calculation
Maximum Rated Power (P)	500,000 kW	Thorcon
Total Construction Cost, *Kc*	$848,370,564.69	Calculation

The study's inputs and parameters were sourced from credible references to ensure realistic expectations for the NPP. Key data, including project duration and PPA tariff, came from Thorcon Indonesia, while transmission loss and auxiliary use followed US EIA standards. Financial metrics, such as equity proportions and cost of equity, were based on Lazard and calculations, with inflation and tax rates from Bank Indonesia and PWC Indonesia. This diverse sourcing ensures reliability and contextual relevance. The financial model follows Build-Own-Operate-Transfer mechanism with 30 years expected PPA agreement (Table 2).

Table 2. Inputs and Assumptions

No	Input/Assumption	Value	Source
1	Project Duration	30 Years (BOOT)	Thorcon
2	Availability Factor	96%	Thorcon
3	Capacity Factor	90%	Thorcon
4	Auxiliary Own Use	5%	(US EIA)
5	Transmission Loss	5%	(US EIA)
6	Degradation Factor	0.50% per year	(NREL, 2012)
7	PPA (Power Purchase Agreement/Tariff)	$6.5 cents per kWh	Thorcon
8	CPI (inflation)	1.71%	(Bank Indonesia, 2024)
9	Equity Proportion	20%	(NEA, 2024)
10	Debt Proportion	80%	Calculation
11	Cost of Equity	12%	(Lazard, 2023)
12	Bank Interest Rate (Investment)	10.36%	(CEIC, September 2024)
13	Corporate (Income) Tax Rate	22%	(PWC Indonesia, 2024)
14	After-tax Cost of Debt	8.08%	Calculation
15	Weighted Average Cost of Capital (WACC)	8.86%	Calculation
16	Tenor Period	15 Years	Thierie, W. and De Moor, L. (2019)
17	Depreciation	3.33%	Calculation
18	Construction Time	3 Years	Thorcon

Table 3 outlines the parameters varied in the Monte Carlo simulation for Value at Risk (VaR) analysis, including capacity factor, fuel cost, overnight construction cost (OCC), power purchase agreement (PPA) tariff, construction time, and availability factor. Each parameter is assigned a probability distribution—normal or empirical—based on referenced studies to reflect real-world uncertainties. The simulation was conducted using Python to generate input values, which were then processed in Excel to calculate outputs such as Net Present Value (NPV), Internal Rate of

Return (IRR), Profitability Index (PI), Discounted Payback Period (DPP), and Levelized Cost of Electricity (LCOE). These parameters were selected based on researcher discussion with experts in energy industry by identifying risks and prioritizing them using risk matrix.

Risks were identified through a combination of a literature review and consultations with experts from Thorcon, as well as a former PT PLN employee with over a decade of experience. Following this, the author prioritized the 18 identified risks using a risk matrix, assigning scores based on their likelihood and potential impact. The critical risks highlighted included prolonged construction timelines, challenges with public perception, disruptions in fuel supply, shifts in policy, and reductions in thermal efficiency.

Table 3. Affected Financial Model Parameters

No	Variable	Distribution	Source	Value on The Source	Real Value by November 2024
1	Capacity Factor	Normal	Roques et al. (2006)	µ: 85% σ: 10%	-
2	Fuel Cost	Empirical	(Locatelli et al., 2013).	• 4.3 \$$_{2003}$/MWh • 3.0, 3.5, 4.0 \$$_{2003}$/MWh • 4.35 \$$_{2004}$/MWh • 4.0, 4.5, 5.0 \$$_{2007}$/MWh • 3.5, 4.0, 4.5 \$$_{2007}$/MWh	• 7.37 \$/MWh • 5.14, 6.00, 6.86 \$/MWh • 7.27 \$/MWh • 6.09, 6.85, 7.61 \$/MWh • 5.33,6.09, 6.85 \$/MWh
3	OCC	Normal	Roques et al. (2006)	µ: 1140 £$_{2005}$/kW σ: 200 £$_{2005}$/kW	µ: 1972.30 £/kW σ: 346.02 £/kW
4	PPA	Normal	Roques et al. (2006)	µ: 40 £$_{2005}$/MWh σ: 10 £$_{2005}$/MWh	µ: 69.20 £/MWh σ: 17.30 £/MWh
5	Construction Time	Empirical	IAEA (2021)	-	-
6	Availability Factor	Empirical	IAEA PRIS (2023)	-	-

5. Results and Discussion

5.1 Numerical Results

The analysis reveals that the project's Net Present Value (NPV) under adverse conditions can drop to -\$442.23 million. This negative NPV indicates that the project would result in a significant financial loss, potentially leading to reconsideration or renegotiation of project terms by stakeholders. The undefined Discounted Payback Period (DPP) highlights cash flow instability and the inability to recover initial investments under unfavorable conditions. Such scenarios emphasize the necessity of robust risk mitigation strategies, including securing stable Power Purchase Agreements (PPAs), efficient construction management, and flexible financial planning.

Furthermore, the stark contrast between the base case and Value-at-Risk (VaR) outputs underscores the financial vulnerability of the project. For example, while the base case suggests a profitable venture with an NPV of \$338.66 million and an IRR of 13.6%, adverse scenarios reduce the IRR to 5.26%, signaling reduced financial appeal. The Profitability Index (PI) also drops significantly from 1.4 to 0.7, indicating a transition from a financially viable project to one that may no longer justify the investment. Additionally, the Levelized Cost of Electricity (LCOE) increases from \$0.0476/kWh to \$0.084/kWh, reflecting heightened cost pressures and reduced competitiveness against alternative energy sources. Addressing these vulnerabilities through targeted strategies is essential to ensure project feasibility and stakeholder confidence (Table 4).

Table 4. Financial Model and Value-at-Risk Output on Investment Indicators and LCOE

No	Parameter	Base Case	Value At Risk
1	NPV	$338,662,809.89	-$ 442,225,922.28
2	IRR	13,60 %.	5.26 %
3	DPP	11.19 Years	NaN
4	PI	1.40	0.70
5	LCOE	0.0476 $/kWh	0.084 $/kWh

5.2 Graphical Results

The Monte Carlo VaR analysis illustrates the financial uncertainties of nuclear power investments across key indicators—NPV, IRR, DPP, PI, and LCOE. At the 95% confidence level, the results reveal potential downside risks: the NPV shows scenarios of significant losses, IRR could drop to as low as ~5%, and the DPP extends considerably, reflecting delayed cash recovery. The profitability index (PI) indicates a potential for falling below 1, highlighting instances where projects could lose profitability, while the LCOE increases to approximately $0.084/kWh, reflecting cost pressures in adverse scenarios.

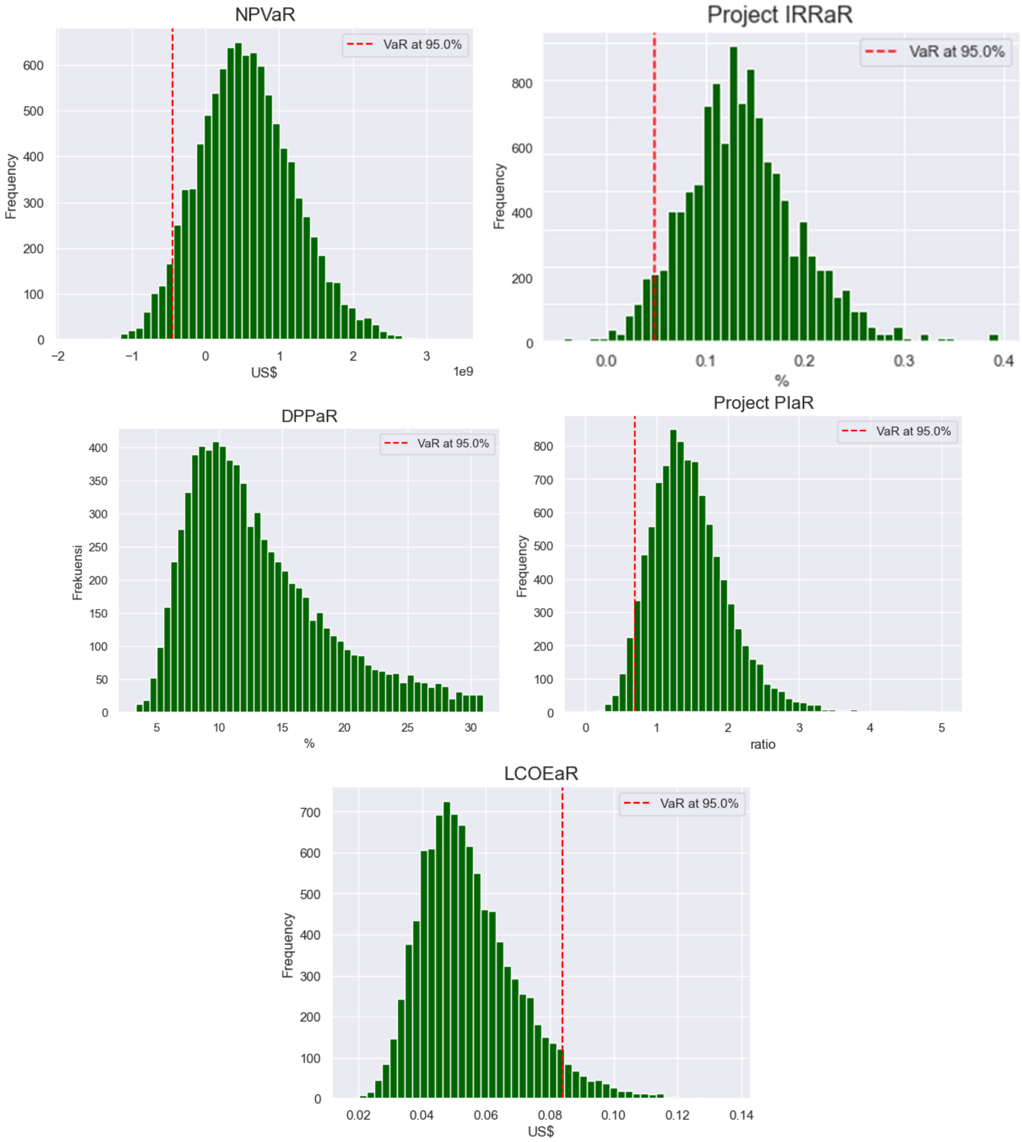

Figure 1. VaR Monte Carlo Output on Investment Indicators and LCOE

However, the analysis also underscores the robustness of the project under typical conditions. Most output remains in a relatively safe range: the NPV stays positive in the majority of simulations, the IRR consistently exceeds the weighted average cost of capital (WACC) of 8.86%, and the PI is predominantly greater than 1. Additionally, the LCOE remains below $0.07/kWh for most cases, emphasizing cost efficiency compared to coal-based power generation, even under risks and uncertainties. These findings highlight both the inherent risks and the resilience of nuclear power investments, suggesting the need for proactive risk management strategies to ensure financial viability (Figure 1).

5.3 Proposed Improvements

The correlation Table 5 highlights several critical relationships that underpin the financial and operational performance of nuclear power plant projects. PPA stability exhibits a strong positive correlation with NPV (0.72) and IRR (0.72), reflecting its critical role in ensuring consistent revenue streams. Any instability in PPA terms, such as renegotiations or market volatility, can significantly undermine profitability, emphasizing the need for robust contractual frameworks.

Overnight Construction Costs (OCC) are positively correlated with LCOE (0.53) and negatively correlated with both NPV (-0.31) and IRR (-0.31). These relationships highlight how high initial costs directly increase electricity generation expenses while eroding overall project returns. Delays in construction, as indicated by the modest positive correlation with LCOE (0.13), exacerbate these financial pressures by escalating costs and deferring revenue generation. Operational efficiency factors, such as the availability factor (0.43 for NPV and 0.41 for IRR), play a pivotal role in maximizing returns. A higher availability factor ensures that the plant operates closer to its maximum capacity, thus reducing LCOE (-0.71) and enhancing financial metrics. Similarly, the capacity factor shows a negative correlation with LCOE (-0.49), reinforcing the importance of optimizing plant performance to achieve cost efficiency.

The Discounted Payback Period (DPP) reveals an inverse relationship with NPV (-0.91) and IRR (-0.86), illustrating that shorter payback periods are associated with more financially attractive projects. Conversely, delays or inefficiencies that extend the DPP can deter investment by increasing financial risk. The interconnectedness of these variables underscores the necessity of addressing risks holistically. For instance, improving construction management to reduce OCC and timelines not only lowers LCOE but also positively impacts NPV and IRR. Similarly, ensuring stable and fair PPA terms and maximizing operational efficiency through high availability and capacity factors can significantly enhance financial viability (Table 5).

Table 5. Spearman Correlation of Combined Risk

	Capacity Factor	PPA	OCC	Fuel	Construction Time	Availability Factor	NPV	IRR	DPP	PI	LCOE
Capacity Factor	1.00										
PPA	-0.06	1.00									
OCC	0.20	0.08	1.00								
Fuel	0.11	-0.10	-0.13	1.00							
Construction Time	0.01	0.05	0.11	0.00	1.00						
Availability Factor	0.27	-0.04	-0.03	-0.09	0.12	1.00					
NPV	0.31	0.72	-0.31	-0.01	-0.07	0.43	1.00				
IRR	0.28	0.72	-0.31	0.00	-0.07	0.41	0.97	1.00			
DPP	0.06	-0.56	0.22	0.12	0.00	-0.23	-0.91	-0.86	1.00		
PI	0.27	0.70	-0.33	0.00	-0.08	0.39	0.96	0.99	-0.84	1.00	
LCOE	-0.49	0.11	0.53	-0.12	0.13	-0.71	-0.58	-0.56	0.30	-0.56	1.00

5.4 Validation

The model's validity is ensured through Monte Carlo simulations with 10,000 iterations, capturing a wide range of outcomes and reducing outlier influence. The integration of normal and empirical distributions reflects key uncertainties, while Spearman correlation coefficients confirm alignment with economic principles, such as the strong link between PPA and NPV/IRR. This paper parameters and results also confirmed and validated to experts.

6. Conclusion

Through the integration of discounted cash flow analysis and Monte Carlo simulations, this study successfully assessed the financial feasibility of a renewable energy investment project under various uncertainty factors. The research objectives outlined at the beginning of the study were fully achieved, including identifying critical risk factors and quantifying their impacts on key financial indicators such as NPV, IRR, and LCOE.

The study demonstrated the utility of Value at Risk (VaR) as a comprehensive risk assessment tool, providing stakeholders with actionable insights into the financial risks and potential returns associated with the project. By incorporating a robust analytical framework, this research uniquely contributes to the understanding of financial feasibility in renewable energy investments, particularly under scenarios of uncertainty.

These findings not only validate the viability of the proposed investment but also highlight the importance of incorporating probabilistic methods to enhance decision-making. The study's innovative approach and detailed analysis serve as a valuable reference for policymakers, investors, and researchers in advancing renewable energy development.

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Biographies

Randy Akmalsyah is a final-year Industrial Engineering student at the University of Indonesia with a passion for sustainability, technology, and finance. He has completed projects in financial modeling and policy analysis, including a silver medal-winning carbon capture initiative in the iGEM Indonesian League 2023. Randy has also interned at Indonesia's Ministry of National Development Planning (Bappenas), contributing to risk mitigation strategies for national development. His research interests include System Engineering, Industrial Simulation, and System Dynamics.

Armand Omar Moeis is an Assistant Professor in the Industrial Engineering Department at the University of Indonesia, specializing in system modeling, industrial simulation, and system dynamics. He holds a Bachelor's degree from the University of Indonesia, a Master's in Engineering and Policy Analysis from Delft University of Technology, and a Doctorate from the University of Indonesia. His research focuses on applying advanced modeling and system thinking to public services and energy systems. In addition to his academic role, Omar actively engages with business and governmental communities, bridging the gap between academia and industry. His contributions include numerous journal publications, conference papers, and collaborative projects in engineering and policy analysis.

Eddie Widiono Soewondho is a seasoned energy expert and former President Director of PT Perusahaan Listrik Negara (PLN), Indonesia's state-owned electricity company. With decades of experience, he has led transformative initiatives in electrification, renewable energy integration, and operational efficiency to advance Indonesia's energy security. Eddie holds degrees in Electrical Engineering from Bandung Institute of Technology (ITB) and an MBA from Prasetiya Mulia Business School, reflecting his interdisciplinary expertise in engineering and business management.