International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(4), 24-33.

Estimation of Levelized Cost of Energy for Small Modular Reactors in Colombia: A Monte Carlo Simulation Approach

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Received: 23 January 2025 **Accepted:** 22 May 2025 **DOI:** https://doi.org/10.32479/ijeep.19364

ABSTRACT

Small modular reactors (SMRs) offer significant prospects for Colombia to diversify and decarbonize its energy mix by 2038, as specified in the National Energy Plan (PEN) 2022-2052. However, current assessments primarily focus on capital expenditure (CAPEX) indicators, such as the overnight capital cost (OCC), while overlooking the Levelized cost of energy (LCOE), which provides a more comprehensive measure of long-term economic viability. This study employs a Monte Carlo simulation to calculate the LCOE of a 300 MW SMRs in Colombia for the 2038-2042 period, including probabilistic distributions for OCC, operational expenditures (OPEX), fuel cost, and capacity factor. The results indicate a median LCOE of \$77.71/MWh, with a range from \$68.26/MWh in optimistic scenarios to \$117.80/MWh in pessimistic ones. These findings suggest that SMRs could serve as a cost-competitive alternative to coal-fired power plants, particularly when externalities such as carbon emissions are considered. Sensitivity analysis identifies OCC and the weighted average cost of capital (WACC) as the most influential cost drivers. Additionally, fuel procurement strategies, including reprocessed fuel and long-term contracts, can further reduce operational costs. This study underscores the importance of integrating LCOE into energy planning and calls for regulatory and financial mechanisms to support SMRs deployment in Colombia.

Keywords: Small Modular Reactor, Levelized Cost of Energy, Monte Carlo Simulation, Energy Transition, Nuclear Energy
JEL Classifications: Q41, Q42, L94

1. INTRODUCTION

The growing need for clean, reliable, and flexible energy solutions has positioned small modular reactors (SMRs) as a promising alternative within the global energy landscape (IEA, 2020). In Colombia, the integration of SMRs aligns with national efforts to diversify the energy matrix, strengthen energy security, and meet international commitments to reduce greenhouse gas emissions. The national energy plan (PEN) 2022-2052 outlines the potential inclusion of SMRs by 2038 as part of Colombia's broader energy transition strategy (UPME, 2022). However, existing assessments by the mining and energy planning unit (UPME) predominantly rely on capital expenditure (CAPEX) metrics, particularly the overnight capital cost (OCC), potentially leading to biased evaluations that overlook the comprehensive economic viability of nuclear technologies.

The levelized cost of energy (LCOE) provides a more robust and holistic measure of economic feasibility, encompassing all costs associated with electricity generation throughout a plant's lifecycle, including capital, operational, maintenance, and fuel expenditures (Friedl et al., 2023). Despite the relevance of LCOE in assessing long-term viability, limited research has been conducted on its application to SMRs in Colombia. Moreover, given the inherent uncertainties in cost parameters, operational conditions, and financing structures, traditional deterministic approaches may not adequately capture the full range of potential outcomes for SMR deployment (Ingersoll and Carelli, 2021).

Nuclear power, including SMRs, exhibits distinct economic characteristics compared to other electricity generation technologies (Moore and Hughes, 2021). While nuclear plants require high initial capital investment, they benefit from relatively low fuel and operational costs, enabling cost competitiveness over their lifecycle (Nian and Yuan, 2021). In contrast, fossil fuel-based plants are often exposed to fuel price volatility, while intermittent renewable sources incur additional system costs due to their reliance on energy storage or backup generation (Locatelli et al., 2014). In liberalized electricity markets, financing high-CAPEX projects such as SMRs poses a challenge, as short-term price signals often deter investors from committing to long-term infrastructure investments. Consequently, innovative financing mechanisms, such as government-backed contracts for difference (CfD) and risk-sharing models, are increasingly being explored to support nuclear deployment (UK Government, 2024).

The transition from coal-fired power plants to SMRs offers a low-carbon electricity generation alternative, significantly contributing to climate change mitigation and improved air quality (Zhen, 2023). Their modular design and smaller size enable deployment at sites previously occupied by coal plants, leveraging existing infrastructure and minimizing implementation costs International Atomic Energy Agency (IEA, 2020). This adaptability makes SMRs an attractive option for facilitating a coal-to-nuclear transition in the energy landscape (González-Salazar et al., 2023). Deploying SMRs in Colombia would not only diversify the national energy matrix but also strengthen energy security and stimulate economic development through the creation of specialized jobs in the nuclear sector (Bistline et al., 2022). However, to realize this transition, it is essential to conduct comprehensive economic evaluations and establish regulatory frameworks that encourage investment and operation of SMRs within the Colombian context (Dixon and Granda, 2021).

This study addresses these gaps by employing the Monte Carlo simulation methodology to estimate the LCOE of SMRs in the Colombian context. By incorporating probabilistic distributions for key variables such as CAPEX, OPEX, fuel costs, and capacity factor, the analysis delivers a statistically robust understanding of the economic performance of SMRs under various scenarios (Müller and Möst, 2021). Additionally, the analysis examines the impact of fuel strategies, sensitivity to critical cost drivers, and scenario-based evaluations, offering valuable insights for policymakers and stakeholders considering nuclear energy as part of Colombia's sustainable energy future.

Ultimately, this research underscores the importance of adopting LCOE as a central metric in energy planning and investment decisions. It advocates for a nuanced approach that accounts for operational flexibility, emission reductions, and the modular advantages of SMRs, all of which contribute to a resilient, low-carbon energy infrastructure tailored to Colombia's unique socio-economic and geographic context.

2. METHODOLOGY

Estimating the LCOE of SMRs in Colombia requires a methodological approach that captures the complexity and inherent uncertainties of long-term energy projects. This section describes the adopted methodological framework, based on Monte Carlo simulation, a powerful tool that models the variability of costs and key parameters to derive a reliable range of results (Steigerwald et al., 2023).

In addition to detailing the fundamental formulas and variables for calculating the LCOE, this chapter explains the assumptions made, the data sources used, and the probabilistic distributions assigned to the main variables. This approach not only ensures a robust economic evaluation but also provides a comprehensive sensitivity analysis, identifying the critical factors that influence generation costs (Abou-Jaoude and Shirvan, 2021).

2.1. Mathematical Description

The LCOE is a metric used to evaluate the average cost of generating a unit of electricity over the lifetime of a project, integrating all associated costs. Key components include CAPEX, which accounts for the initial costs of construction and installation (Ganda and Kim, 2021). These are calculated using the OCC, a measure that estimates the cost of constructing the plant as if it were completed "overnight," excluding financial interests and inflation adjustments. On the other hand, OPEX (Operational Expenditure) covers operational and maintenance costs (both fixed and variable) as well as fuel costs throughout the project's lifecycle (Boungiorno and Parsons, 2021).

In addition, the LCOE incorporates the plant's capacity factor, the reactor's lifespan, and applies a discount rate to calculate the present value of all future cost and benefit flows. This metric is fundamental because it provides a comprehensive and comparable view of generation costs across different energy technologies, enabling informed and strategic decision-making.

The LCOE is calculated as the average cost of generation per unit of energy over the plant's lifetime. Its basic formula is:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+WACC)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+WACC)^t}} \tag{1}$$

Where,

I_t is investment expenditures in year t
M_t is operations and maintenance expenditures in year t
F_t is fuel expenditures in year t
E_t is electrical energy generated in year t
$WACC$ is Weighted Average Cost of Capital
n is expected lifetime of the system or power station.

2.1.1. WACC estimation

The weighted average cost of capital (WACC) represents the average rate of return required by both debt and equity investors to finance a company's assets or a specific project. It is a key financial metric used in investment decision-making, capital budgeting, and valuation models (Roques and Savva, 2021). A lower WACC indicates a lower cost of capital, enhancing project feasibility, whereas a higher WACC suggests increased financial risk and a higher capital cost.

The incorporation of the social discount rate (SDR) into WACC enables a more comprehensive evaluation of projects with long-term social benefits, such as renewable energy and infrastructure investments (Kümmel, 2011). Unlike market-driven discount rates, the SDR accounts for intergenerational equity and the broader economic impact of investments. By integrating the SDR into WACC, decision-makers can better prioritize projects that may not be immediately profitable from a private investment standpoint but generate significant social and environmental value over time (Koller et al., 2020). This approach is commonly referred to as social WACC.

However, a key limitation of this model is that it tends to underestimate the uncertainties associated with emerging technologies. For this study, the general mathematical model of WACC is preferred, as it employs the cost of capital without the distortions introduced by the social discount rate using the following formula:

$$\mathrm{WACC} = \left(\frac{D}{D+E} \times r_d \times (1-T)\right) + \left(\frac{E}{D+E} \times r_e\right) \tag{2}$$

Where,

D is total debt, amount of financing obtained through loans or bonds.

E is total equity, amount of financing obtained from investors or retained earnings.

r_d is cost of debt, interest rate on debt financing.

r_e is cost of equity,

T is corporate tax rate, since interest on debt is tax-deductible, this adjusts for tax savings.

The cost of equity r_e was estimated using the capital asset pricing model (CAPM) (Poncet and Portait, 2022), which follows the formula:

$$re = rf + (rm - rf) \tag{3}$$

Where:

r_f is risk-free rate

r_m is expected market return

β is systematic risk of the investment

$r_m - r_f$ is market risk premium

For this study, the risk-free rate (r_f) was set at 2%, based on the yield of U.S. Treasury Bonds. This selection is justified by the fact that these instruments are globally regarded as the safest financial assets, with minimal credit risk and high liquidity. While Colombian government bonds (TES) could have been considered, their yields incorporate the country's sovereign risk, which would misalign the calculation with international investment assessments.

The beta coefficient (β) was set at 1.2 to capture the systematic risk associated with SMR projects. Traditional power generation companies typically exhibit betas ranging between 0.6 and 1.0, as they operate in highly regulated markets with stable revenue streams. However, SMRs represent an emerging technology with limited commercial deployment, introducing additional technological and regulatory uncertainties. As a result, a β above 1.0 was selected to reflect the higher risk profile associated with SMR investments, while avoiding excessive deviation from conventional energy sector benchmarks (Boarin et al., 2015).

Given that SMR financing involves both domestic and international investors, a widely recognized and stable benchmark was preferred. The expected market return (r_m) was assumed to be 9%, reflecting the historical performance of Colombia's stock markets. Studies on the long-term returns of the MSCI Colombia Index and COLCAP suggest that stock market performance fluctuates between 7% and 10%, depending on macroeconomic conditions (Mariño and Melo-Velandia, 2025). Therefore, a 9% value was deemed a reasonable estimate. A market risk premium (r_m - r_f) of 7% was assumed as a balanced representation of Colombia's market conditions (Damodaran, 2024). This value aligns with empirical studies indicating that risk premiums in these economies generally range between 6% and 9%, accounting for factors such as inflation volatility, currency risk, and geopolitical uncertainty.

Using the formula (3), the cost of equity (r_e) was determined to be 10.4%, a higher value than that of renewable energy projects due to the perceived technological and regulatory risks of SMRs. A capital structure typical for infrastructure projects was assumed, consisting of 70% debt (*D*) and 30% equity (*E*) (CRA, 2005). The cost of debt (r_d) was set at 10%, derived from the Colombian fixed-term deposit rate (DTP) of 6% plus a 4% risk premium, while the corporate income tax rate (*T*) was established at 35%. Using the corresponding formula (2), the WACC was determined to be 10.4%.

2.2. Calculation Methods

The Monte Carlo methodology is particularly suitable for energy projects due to the inherent uncertainty of many variables that affect costs and electricity generation. In this analysis, it is used to estimate the LCOE of SMRs in Colombia by incorporating a range of possible values for key parameters such as CAPEX, OPEX, fuel costs, construction time, and capacity factor (Weimar et al., 2021). This probabilistic approach allows for exploring how variability in these inputs impacts the final results, providing not only an average LCOE value but also a complete range of outcomes and their associated probabilities.

In this study, each variable was assigned a probabilistic distribution based on values provided by the meta-analysis conducted by Idaho National Laboratory (2024). For instance, CAPEX was modeled using a triangular distribution to better capture uncertainties in initial construction costs, while operating and maintenance costs (both fixed and variable) were modeled with a normal distribution, reflecting a probable range based on previous experiences. Fuel costs, which tend to exhibit fewer extreme variations, were assigned a uniform distribution to evaluate potential changes within a known interval. The capacity factor was held constant at reference value of 0.93.

This analysis involved running 10,000 iterations for each scenario (optimistic, baseline, and pessimistic), providing a statistically robust representation of the expected LCOE. This approach not only identifies the mean or median LCOE but also evaluates the probability of reaching specific cost thresholds, which is critical for decision-making in projects with high upfront investment and long evaluation horizons. In addition to the central values, the Monte Carlo methodology includes a subsequent sensitivity analysis. This step identifies which variables have the greatest impact on LCOE outcomes. For example, the discount rate and capital costs are typically the most critical variables in nuclear projects, and understanding their influence is essential for designing strategies to mitigate financial risks or enhance the economic competitiveness of SMRs in Colombia.

To estimate the LCOE of SMRs, one of the fundamental variables is the OCC, which, in this analysis, is considered as between a first and Nth of a kind, (BOAK). This concept refers to the initial costs associated with the first reactors built, reflecting both the learning curve and the technical and economic challenges of novel projects (IEA, 2021). Using BOAK values is crucial as it provides a realistic perspective of the costs faced by early adopters of this technology. The OCC for 2038 was estimated through an interpolation between OCC values for 2024 and 2050. To account for expected cost reductions while maintaining a conservative approach, the interpolation assigns a weight of 70% to the 2024 BOAK OCC and 30% to the projected 2050 OCC. This ensures that the model considers both technological advancements and potential cost overruns.

In this study, BOAK and OCC values were sourced from a meta-analysis conducted by the Idaho National Laboratory (INL) Digital Library (2024), ensuring that the data used is based on a broad range of projects and international scenarios. This approach allows for cost evaluations grounded in consolidated prior experiences, minimizing biases and providing a reliable range for the simulations. The integration of these data enhances the accuracy and relevance of the model when applied to the Colombian context (Table 1).

Defining probabilistic distributions for key variables is essential in Monte Carlo simulations to accurately capture uncertainties in cost estimation and operational parameters. Capital costs, such as OCC, follow a triangular distribution, reflecting expert-defined ranges, while O&M costs typically follow a normal distribution due to their stability. Fuel costs, influenced by market fluctuations, are best modeled with a uniform distribution. Proper distribution selection ensures robust LCOE estimates, reducing bias and improving decision-making for SMR deployment. This structured approach enhances the reliability of financial assessments, as shown in Table 2.

Table 1: Key data from INL digital library

Variable	Advance	Moderate	Conservative
BOAK OCC ($/kWe)	5,500	8,000	10,000
OCC 2050 ($/kWe)	2,000	4,000	6,250
Fuel costs ($/MWh)	10.0	11.0	12.1
Fixed O&M ($/kW-year)	118	136	216
Variable O&M ($/MWh)	2.2	2.6	2.8
Power output (MWe)	300		
Capacity factor	0.93		
Construction time (months)	43	55	71
Ramp rate (%/min)	10		

Data from: Abou-Jaoude et al., 2024

Table 2: Probability distributions assigned to key variables

Variable	Probabilistic distribution	Source
BOAK OCC ($/kWe)	Triangular	Schröder and Kuckshinrichs (2015)
OCC 2050 ($/kWe)	Triangular	Mathews et al. (2007)
Fuel Costs ($/MWh)	Uniforme	Kim and Taiwo (2013)
Fixed O&M ($/kW-year)	Normal	IAEA (2018)
Variable O&M ($/MWh)	Normal	Locatelli et al. (2013)
Power output (MWe)	Fixed	IAEA (2013)
Capacity factor	Fixed	Ingersoll (2009)
Construction time (months)	Triangular	Berthelemy and Rangel (2015)
Ramp rate (%/min)	Normal	Khoshahval and Sepanloo (2014)

2.3. Modeling Tools

Computational modeling tools were employed to conduct the analysis, allowing for the handling of probabilistic distributions and large-scale stochastic simulations. The model was implemented in Python using libraries such as NumPy, Matplotlib, and Seaborn, renowned for their capacity to perform precise and efficient calculations in Monte Carlo simulations (Hill et al., 2022).

The probabilistic approach ensures that not only point estimates of the LCOE are obtained, but also confidence ranges and full distributions, which are essential for capturing the inherent uncertainty of energy infrastructure projects (Egieya et al., 2023). Additionally, sensitivity analysis was integrated into the simulation process, enabling the identification of the most influential variables affecting the LCOE outcome (Saltelli et al., 2019). This approach facilitates the prioritization of interventions or mitigation strategies, such as government incentives or improved financing conditions, which can significantly reduce overall costs. The use of these tools not only adds precision to the analysis but also enhances the interpretability of the results by providing a comprehensive perspective on risks and opportunities (Asuega et al., 2023). This is particularly valuable for informing energy policymakers and for building a robust framework to support the inclusion of SMRs in Colombia's energy mix. The ability to adjust distributions and scenarios based on more specific data also ensures that this model can be adapted to future developments in the country's energy sector.

3. FINDINGS

3.1. LCOE Probability Distribution for SMR in Colombia 2038-2043

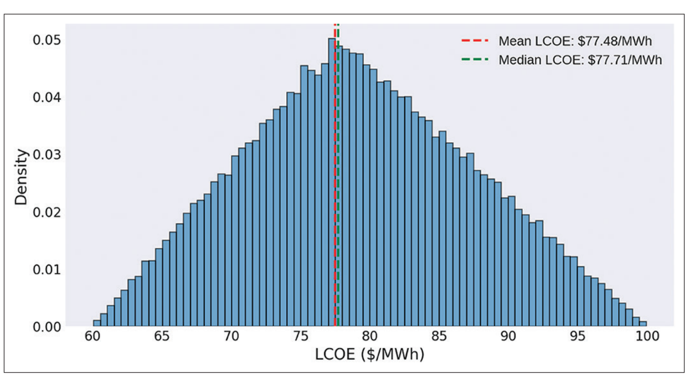
The LCOE values obtained through the Monte Carlo simulation can be considered representative for the 2038-2043 period due to the statistical properties of the distribution and the methodological approach applied. The proximity between the mean (77.48 $/MWh) and the median (77.71 $/MWh) indicates a nearly symmetric distribution with minimal skewness of 0.03, suggesting that the results are not significantly influenced by extreme values or outliers. Additionally, the standard deviation of 8.60 $/MWh and a coefficient of variation of 11.1% confirm that the spread of possible LCOE values remains within a reasonable range, reinforcing the robustness of the estimate. The kurtosis value of 3.02 further indicates that the distribution closely resembles a normal distribution, with no excessive tails or extreme outliers affecting the results.

Monte Carlo simulations inherently smooth out short-term variability by averaging a large number of probabilistic iterations, reducing the impact of stochastic noise on the final result. Given that 100,000 iterations were performed, the distribution reflects a stable long-term projection rather than short-term fluctuations (Gentle, 2020). Furthermore, key cost parameters, such as the WACC (10.4%) and the capacity factor (0.93), were kept constant, eliminating financial and operational variability that could introduce additional uncertainty.

Following the methodology adopted by the International Energy Agency (IEA), which reports LCOE values in 5-year intervals, the results of this study align with standard industry practices for energy cost assessment (IEA and NEA, 2020). Since SMRs are expected to begin operation in 2038, their cost structure should remain relatively stable during the initial years of deployment, supporting the assumption that the estimated LCOE is applicable for the 2038-2043 timeframe Figure 1.

The results also hold significant implications when compared to other technologies. Renewable energy sources, such as solar photovoltaic and wind, can achieve low LCOE values, but their generation capacity is intermittent and depends on external factors like weather. This intermittency often necessitates additional storage or backup systems, which increase their effective costs. On the other hand, large reactors (LR) tend to have lower LCOE due to economies of scale, but they require significantly higher initial investments and longer construction timelines, which may complicate their implementation in developing countries like Colombia.

Figure 1: Levelized cost of energy probability distribution for small modular reactors in Colombia 2038-2043



3.2. Sensitivity Analysis of LCOE

The univariable sensitivity analysis for the LCOE of a 300 MW SMR in Colombia confirmed that the OCC is the most influential factor affecting electricity generation costs. The Pearson correlation coefficient between OCC and LCOE was 0.9986, demonstrating a nearly perfect linear relationship. This result aligns with expectations for nuclear energy projects, where high upfront capital expenditures dominate total project costs. Fuel costs, when considered independently, exhibited a lower correlation of 0.0488, suggesting a limited direct influence on LCOE in isolation. Similarly, fixed and variable O&M costs showed minimal individual effects, with correlations of −0.0014 and 0.0079, respectively. These findings emphasize that reducing OCC—whether through optimized construction schedules or modular fabrication techniques—would be the most effective strategy for lowering LCOE. The capacity factor and WACC were held constant in this simulation; therefore, their potential contributions to variability require further investigation. However, the multivariable sensitivity analysis provided additional insights into the interplay between different cost components. When fuel costs and variable O&M costs were assessed in conjunction with OCC, their relative influence increased, each contributing approximately 49.76% of the total impact. This result highlights that while OCC remains the dominant factor in isolation, operational considerations such as fuel procurement strategies and efficiency improvements in O&M become equally critical when analyzed in combination. Notably, the relative importance of OCC decreased significantly in the multivariable context, contributing only 0.47% to the overall LCOE variation. Meanwhile, fixed O&M costs continued to exhibit minimal influence, representing only 0.0061% of the total impact.

From Table 3, it can be inferred that although fuel costs have a minor direct impact in a univariable analysis, their effect becomes more pronounced when integrated into a broader cost structure. This observation aligns with the scenario-based fuel strategy assessment, which demonstrated that different procurement models can yield notable reductions in LCOE. Consequently, effective LCOE optimization requires a comprehensive approach that balances capital cost reductions with strategic operational planning, including fuel supply management and efficiency improvements in plant operations.

Table 3: Sensitivity analysis results

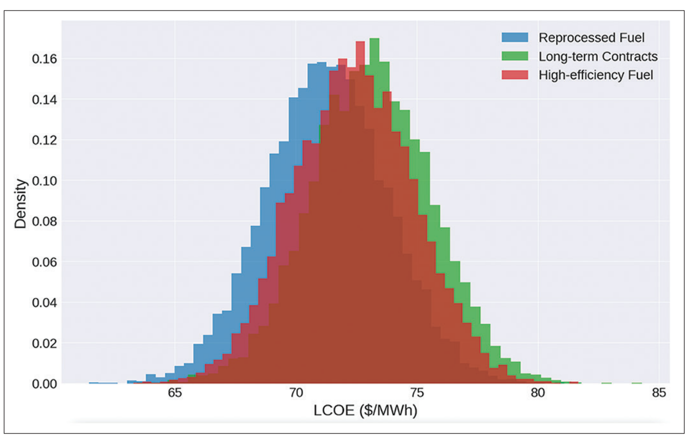
Variable	Pearson correlation (univariable)	Regression coefficient (multivariable)	Normalized coefficient (%)
OCC ($/kWe)	0.9986	0.47	0.47
Fixed O&M ($/kW-year)	−0.0014	0.0061	0.0061
Variable O&M ($/MWh)	0.0079	49.76	49.76
Fuel Cost ($/MWh)	0.0488	49.76	49.76

3.3. Impact of Fuel Strategies on LCOE

To further assess the influence of operational factors, particularly fuel management, an additional analysis was conducted to evaluate the impact of different fuel strategies on the LCOE. Three scenarios were considered: reprocessed fuel, long-term contracts, and high-efficiency fuel. The scenario using reprocessed fuel resulted in the lowest mean LCOE of 71.26 $/MWh. This significant reduction compared to the base scenario reflects the lower fuel costs associated with reprocessing. However, implementing this strategy may involve overcoming technological and regulatory challenges related to handling and safety. The long-term contracts strategy achieved a mean LCOE of 73.09 $/MWh as depicted in Figure 2. Although this scenario had a slightly higher LCOE than the reprocessed fuel case, it provides enhanced cost predictability by mitigating risks associated with fuel price volatility, making it particularly attractive for long-term infrastructure investments. The high-efficiency fuel scenario resulted in a mean LCOE of 72.43 $/MWh, representing a balanced approach as shown in Table 4. This strategy reduces total fuel consumption by improving fuel performance, leading to lower operational costs without significant technological complexity.

The comparative analysis of these fuel strategies demonstrates that fuel management decisions can substantially influence the economic performance of SMRs. Although the univariable sensitivity analysis initially suggested that fuel costs have a limited impact on LCOE, the scenario analysis shows that practical fuel strategies can alter cost structures significantly. The reprocessed fuel scenario offers the most substantial reduction in LCOE, making it an economically attractive option despite its associated complexities. Long-term contracts provide a pragmatic solution, securing fuel supply and stabilizing costs, while high-efficiency fuels present a viable balance between operational efficiency and cost. Overall, these findings emphasize that a comprehensive approach combining capital cost reductions with strategic fuel management is essential for achieving competitive LCOE levels for SMRs in Colombia.

Figure 2: Levelized cost of energy distribution for different fuel strategies



3.4. Scenario Analysis

The analysis focused on three distinct scenarios: Optimistic, base, and pessimistic, each defined by varying assumptions regarding capital costs, operational expenditures, fuel costs, and capacity factors. These scenarios provide a comprehensive understanding of how key parameters influence the economic viability of SMR deployment in the Colombian energy market.

In the optimistic scenario, favorable conditions were assumed, including reduced OCC, lower O&M costs, and a high-capacity factor of 0.95. Under these assumptions, the LCOE mean was 68.26 $/MWh, with a median value of 68.27 $/MWh. The standard deviation of 3.81 $/MWh indicates low uncertainty, and the 5th to 95th percentile range of 61.87-74.63 $/MWh highlights strong cost predictability. This scenario demonstrates the potential for SMRs to achieve highly competitive LCOE values, particularly when leveraging advanced fuel technologies, efficient construction processes, and favorable financing conditions.

The base scenario represents realistic market conditions, utilizing standard assumptions for OCC, O&M costs, fuel expenses, and a capacity factor of 0.93. The LCOE mean was calculated at 77.48 $/MWh, with a median of 77.71 $/MWh. A higher standard deviation of 8.60 $/MWh compared to the optimistic scenario indicates moderate uncertainty. The percentiles ranged from 62.86 $/MWh (5th) to 91.63 $/MWh (95th), suggesting a broader distribution of possible outcomes. This scenario serves as a benchmark for assessing the feasibility of SMR deployment under typical economic and operational conditions as shown in Table 5.

The pessimistic scenario assumed adverse conditions, including elevated OCC, higher O&M and fuel costs, and a lower capacity factor of 0.90. The resulting LCOE mean was 117.80 $/MWh, with a median of 117.20 $/MWh. The standard deviation was 6.18 $/MWh, and the 5th to 95th percentile range extended from 108.40 $/MWh to 128.86 $/MWh. This scenario highlights the

Table 4: Impact of fuel strategies on LCOE

Fuel strategy	Mean LCOE ($/MWh)	Std Dev ($/MWh)	5th Percentile ($/MWh)	Median ($/MWh)	95th percentile ($/MWh)
Reprocessed fuel	71.26	8.60	56.64	71.49	85.41
Long-term contracts	73.09	8.60	58.48	73.31	87.23
High-efficiency fuel	72.43	8.61	57.79	72.66	86.58

Table 5: Scenario analysis results for SMR LCOE

Scenario	Mean LCOE ($/MWh)	Std Dev ($/MWh)	5th percentile ($/MWh)	Median ($/MWh)	95th percentile ($/MWh)
Optimistic	68.26	3.81	61.87	68.27	74.63
Base	77.48	8.60	62.86	77.71	91.63
Pessimistic	117.80	6.18	108.40	117.20	128.86

challenges faced by SMR projects under unfavorable market conditions, where high capital and operational costs could render the technology economically unviable without significant financial support or policy incentives.

The comparison of these scenarios reveals a significant range in potential LCOE values, from 68.26 $/MWh in the optimistic case to 117.80 $/MWh in the pessimistic case. The approximately 50 $/MWh difference underscores the critical impact of capital costs, operational efficiency, and capacity utilization on project economics. The optimistic scenario positions SMRs as a highly competitive energy option when optimal conditions are met. In contrast, the pessimistic scenario demonstrates the economic risks associated with higher costs and lower operational performance.

4. DISCUSSION

SMRs have the potential to play a transformative role in Colombia's energy transition, not only as a complementary option within the energy mix but also as a direct substitute for coal-fired power plants. This transition, known as coal-to-nuclear, could yield significant benefits in terms of emissions, efficiency, and land use, and should be considered a key strategy for decarbonizing the Colombian electricity sector.

In terms of land use intensity, SMRs also offer significant advantages. A typical SMR plant requires less land than a coal plant of equivalent capacity due to reduced needs for auxiliary facilities and fuel storage (Hansen and Dixon, 2022). This is particularly important in a country like Colombia, where available land for energy projects is limited and must compete with other priorities such as agriculture, environmental conservation, and urban development (Lloyd et al., 2018). When comparing LCOE, SMRs can be competitive with coal if social and environmental costs are considered. According to international estimates, the average LCOE for coal plants ranges from $60 to $120/MWh, depending on factors such as plant age, coal type, and carbon capture technology (if implemented). In contrast, the Monte Carlo analysis results indicate that the average LCOE for SMRs in Colombia would be approximately $77.48/MWh, with a range of $68.26/MWh to $117.80/MWh under typical scenarios. This comparison highlights that, even without internalizing the external costs of coal, SMRs are already cost-competitive in terms of generation costs. When the economic impact of emissions and public health issues associated with coal is included, the advantage of SMRs becomes even greater (Carless et al., 2016). The coal-to-nuclear transition would not only contribute to emission reductions and improved air quality but also drive the modernization of Colombia's energy system. Locating SMRs at sites previously used for coal plants could leverage existing infrastructure, such as transmission lines, reducing costs and accelerating implementation. Therefore, it is recommended that Colombia explore specific policies to facilitate this transition, including incentives for coal-to-nuclear projects, international financing for sustainable projects, and technology transfer programs (IEA, 2021).

In light of the analysis conducted, it is recommended that Colombia develop a comprehensive regulatory framework specifically tailored to nuclear energy, particularly for small modular reactors (SMRs). Although Law 1715 of 2014 recognizes nuclear energy as a non-conventional energy source (FNCE) and provides general incentives such as tax deductions, VAT exclusions, and tariff exemptions, additional regulations are necessary to address the unique characteristics and safety requirements associated with nuclear technology (Maronati et al., 2020). Unlike solar and wind energy projects, which have benefited from complementary norms and detailed guidelines clarifying access to incentives, nuclear energy projects require regulations that cover licensing procedures, operational safety standards, radioactive waste management, and institutional responsibilities. Establishing clear regulatory pathways would not only provide legal certainty to investors but also align the country's nuclear initiatives with international best practices.

The use of LCOE as a metric to assess the economic feasibility of SMRs in Colombia has proven to be more comprehensive than relying solely on CAPEX. While CAPEX captures only the initial construction costs, LCOE incorporates all costs throughout the reactor's lifetime, including operation, maintenance, fuel, and associated discount rates. This is particularly relevant for technologies like SMRs, which have high initial costs but distribute their benefits over decades of reliable operation with low carbon emissions. Including LCOE in economic evaluations not only enables comparisons between SMRs and other technologies but also helps identify areas where cost optimization can enhance the competitiveness of this technology (Vinoya et al., 2023).

The inclusion of externalities in the calculation of the Levelized cost of energy (LCOE) for small modular reactors (SMRs) is essential to reflect the environmental costs associated with energy generation. In Colombia, the national carbon tax, established by Law 1819 of 2016 and regulated by Decree 926 of 2017, applies to carbon dioxide equivalent (CO_2eq) emissions derived from the combustion of fossil fuels. Although this tax primarily targets fuels such as gasoline, diesel, and natural gas, its consideration in the context of SMRs is relevant for a comprehensive cost assessment. UNECE (2022) note thar SMRs, including NuScale and Westinghouse's AP300, exhibit significantly low CO_2 emissions during their life cycle compared to fossil fuel power plants. According to recent studies, the life cycle CO_2 emissions for these reactors range from 4.6 to 8.4g CO_2eq/kWh. It is important to note that the IPCC (2014) estimate that coal´s life-cycle greenhouse range from 740 to 910 gCO_2/kWh.

Considering that the carbon tax in Colombia is 25,799 COP per metric ton of CO_2eq (DIAN, 2024), and assuming an emissions intensity of 6.5g CO_2eq/kWh for SMRs based on UNECE data (2022), with an exchange rate of 4,000 COP/USD, it can be concluded that this type of nuclear reactor would incur a carbon tax cost of 0.041 USD/MWh in Colombia. This cost is marginal compared to the total operational costs of an SMR, highlighting its minimal environmental impact in terms of CO_2 emissions. Regarding emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2), nuclear energy produces minimal quantities during their life cycle (Zheng and Tong, 2023). These emissions primarily occur during the mining and processing of nuclear fuel. Compared to fossil fuel-based power plants, the emissions of NO_x and SO_2

from SMRs are considerably lower. Currently, Colombia does not impose direct taxes on NO_x and SO_2 emissions in the energy sector. Given the negligible contribution of SMRs to these emissions, their impact on the LCOE would be insignificant (Wanni et al., 2024).

Furthermore, given the role of SMRs in providing low-emission, reliable baseload power, Colombia should explore the creation of targeted incentive mechanisms specifically designed for nuclear energy. These mechanisms could include preferential financing options, accelerated depreciation benefits, or inclusion in clean energy certificate markets (Carelli and Ingersoll, 2022). Additionally, policies that recognize the contribution of nuclear energy to grid stability and decarbonization goals could enhance its competitiveness within the national energy mix. By implementing a robust regulatory and incentive framework (Dixon and Ganda, 2021), Colombia can position nuclear energy, particularly SMRs, as a key component in achieving its long-term sustainability and energy security objectives, while maintaining alignment with global standards for nuclear safety and environmental responsibility (Nick et al., 2024).

5. CONCLUSION

This study provides a comprehensive economic assessment of SMRs in Colombia by estimating their LCOE for the 2038-2043 period using Mote Carlo simulations. The results indicate that SMRs can achieve a median LCOE of $77.71/MWh, with values ranging from $68.26/MWh in optimistic scenarios to $117.80/MWh under pessimistic conditions. These findings suggest that SMRs can be a competitive alternative to coal-fired power plants, particularly when externalities such as carbon emissions and air pollution costs are considered.

The sensitivity analysis highlights that OCC is the most critical driver of LCOE, with a nearly perfect linear correlation (0.9986). However, when multiple cost factors are analyzed simultaneously, the relative importance of OCC diminishes, and fuel procurement strategies and operational efficiencies gain significance. This underscores the need for an integrated cost management approach that combines capital expenditure optimization with strategic fuel and operational planning.

Fuel strategies, including reprocessed fuel, long-term contracts, and high-efficiency fuels, demonstrated substantial potential for reducing LCOE. Among these, reprocessed fuel achieved the lowest mean LCOE of $71.26/MWh, highlighting its economic attractiveness despite regulatory and technological challenges. The scenario analysis further revealed that under favorable economic and operational conditions, SMRs could reach an LCOE of $68.26/MWh, making them highly competitive in Colombia's electricity market.

Beyond cost competitiveness, SMRs present additional advantages such as land-use efficiency, high-capacity factors, and suitability for replacing retiring coal plants in a coal-to-nuclear transition. These attributes reinforce their role as a viable pathway for decarbonizing Colombia's energy sector while enhancing grid stability.

Given these findings, Colombia should develop a regulatory and financial framework tailored to SMRs. This should include policies that facilitate private investment, financial incentives for nuclear deployment, and streamlined licensing processes. Furthermore, incorporating LCOE as a standard metric in national energy planning would provide a more accurate evaluation of SMRs' long-term economic viability compared to CAPEX-centric assessments.

Therefore, SMRs represent a technically and economically feasible solution for Colombia's energy transition. However, their successful implementation will depend on a combination of cost reduction strategies, supportive policy frameworks, and the alignment of nuclear energy development with broader national sustainability goals.

5.1. Limitations

Although the results provide a robust perspective on the LCOE for SMRs, there are inherent limitations that should be considered. The reliance on secondary data from an international meta-analysis may introduce generalizations that do not fully reflect Colombia's specific context, such as local construction costs or financing conditions. Additionally, the analysis is based on a range of assumptions that, while well-informed, may not capture extreme variations, such as changes in public policies, capital flows, or supply chain disruptions.

One of the primary limitations of the Monte Carlo simulation used to estimate the LCOE for SMRs in Colombia is its implicit assumption of deployment in regions with adequate terrestrial transportation infrastructure, access to productive supply chains, and integration into the national interconnected grid. The model is designed for areas where logistical, construction, and operational costs are minimized due to proximity to essential resources and developed infrastructure. However, this approach does not account for the distinct conditions present in non-interconnected zones, where logistical constraints, limited infrastructure, and isolated energy systems can significantly increase capital expenditures, operational costs, and construction timelines.

5.2. Suggestions for Future Research

Future research should refine LCOE estimates by incorporating localized construction costs and assessing regional infrastructure capabilities, such as transportation networks and energy transmission proximity. This would improve accuracy in evaluating SMRs competitiveness across different regions in Colombia.

Additionally, the deployment of SMRs in non-interconnected zones requires further analysis. Investigating modular deployment strategies, logistical challenges, and community acceptance would clarify the feasibility of SMRs in remote areas lacking grid connectivity. Similarly, advanced fuel strategies merit exploration, including closed fuel cycles, international procurement partnerships, and fuel recycling technologies to enhance economic viability and mitigate geopolitical risks.

Hybrid energy systems integrating SMRs with renewables should also be examined to optimize grid stability and costeffectiveness. Research should model optimal configurations and assess operational synergies. Furthermore, innovative financing mechanisms—such as green bonds and risk-mitigation instruments—warrant study to lower the WACC and improve project bankability.

From a regulatory perspective, comparative analyses of international SMR licensing frameworks and safety standards would aid in streamlining approvals and ensuring compliance with global nuclear governance. Finally, socio-political research on public perception and stakeholder engagement is crucial for fostering social acceptance and facilitating nuclear deployment.

Addressing these areas will support a robust, data-driven strategy for integrating SMRs into Colombia's energy transition, ensuring sustainability, resilience, and alignment with global decarbonization goals.

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