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Modeling the transition from coal to SMRs in Colombia: emissions avoidance under deterministic and probabilistic frameworks

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The coal-to-nuclear strategy offers a promising pathway for decarbonizing Colombia's electricity sector while improving system reliability. This study evaluates the potential CO_2-equivalent (CO_2eq) emission reductions resulting from the replacement of coal-fired power plants with small modular reactors (SMRs) over the period 2035 to 2052. Two methodological approaches were used: a deterministic model based on projected installed capacities, decommissioning schedules, and fixed emission factors; and a stochastic Monte Carlo simulation incorporating uncertainty in emission rates and plant performance. The deterministic model estimates a total of 82.62 $MtCO_2$eq of avoided emissions, while the probabilistic approach yields a median value of 76.04 $MtCO_2$eq with a standard deviation of 6.58 $MtCO_2$eq. These consistent results across both methods demonstrate the robustness of the strategy under different technical assumptions. The findings support the viability of coal-to-nuclear replacement as a key contributor to Colombia's climate goals. In addition to mitigating greenhouse gas emissions, the integration of SMRs could enhance grid resilience by reducing reliance on hydroelectric generation, which is vulnerable to climate variability, and by lowering local air pollution from coal combustion. The analysis underscores the importance of regulatory support and technical planning to enable the deployment of nuclear technologies as part of Colombia's long-term energy transition.

KEYWORDS

energy system decarbonization, small modular reactors, coal-to-nuclear transition, energy transition, energy policy

1 Highlights

- Replacing coal with nuclear power could significantly cut Colombia's future carbon emissions.
- This study compares two models to assess the climate benefits under different assumptions.
- The results support nuclear energy as a stable and clean option for Colombia's energy transition.

2 Introduction

Climate change is among the most urgent environmental and socioeconomic challenges of the 21st century (IPCC 2021). According to the IPCC (2021), limiting global warming to 1.5°C requires a drastic reduction in greenhouse gas emissions, particularly carbon dioxide (CO_2eq). Globally, the energy sector accounts for approximately 40% of these emissions, with coal-fired electricity generation being one of the largest contributors (Kumi and Mahama 2023). In response, many countries have adopted decarbonization strategies that progressively replace fossil fuels with low-carbon technologies, including nuclear energy (Jun et al., 2024). Over the past 5 decades, nuclear power is estimated to have avoided the emission of 70 Gt of CO_2, and it currently avoids more than 1 Gt of CO_2 per year, positioning it as a key technology in the transition to sustainable energy systems (IAEA 2020). Colombia has pledged to mitigate climate change under the Paris Agreement and at COP26, setting a target to reduce its emissions by 51% by 2030 and to achieve carbon neutrality by 2050 (UNFCCC 2022).

However, a review of the energy transition scenario outlined in the National Energy Plan (PEN 2022–2052) reveals an intention to maintain the current installed capacity of coal-fired power plants. The scenario also envisions the introduction of nuclear energy beginning in 2035, with an estimated installed capacity ranging between 1,200 MW and 1,800 MW, to be deployed in 300 MW blocks via small modular reactors (SMRs) technology (UPME 2022). Although renewable energy sources are expanding, the national power system remains heavily reliant on hydropower, which is vulnerable to climate variability and poses risks to long-term energy reliability (Henao et al., 2020).

This study examines the potential of a coal-to-nuclear strategy for Colombia based on the gradual replacement of coal-fired plants with SMRs. A realistic timeline for plant retirement and a phased schedule for nuclear deployment are used, and two complementary models are developed: a deterministic model, which estimates cumulative CO_2eq emission reductions between 2035 and 2052, and a stochastic model, which incorporates uncertainty in key technical parameters such as emission factors and capacity factors through Monte Carlo simulation. The results provide insights into the climate impact of this transition and its potential contribution to meeting Colombia's decarbonization commitments. The analysis draws upon projections from the PEN 2022–2052, IPCC emission factors, the international literature on coal-to-nuclear conversion, and recent studies on the technical and economic feasibility of SMRs in the Colombian context.

3 Conceptual framework

International experience, particularly in China, has shown that converting coal-fired power plants to nuclear facilities can offer economic advantages by reusing existing infrastructure, such as transmission lines, access roads, and cooling systems (Xu et al., 2022; Luo et al., 2024). In Europe and North America, similar initiatives have been considered in countries such as Poland and the United States, where the technical and economic feasibility of this transition has been evaluated within broader energy transition policies (Ochmann et al., 2024; Smith et al., 2024; Jóźwik et al, 2024).

However, most of Colombia's coal plants were built between the 1960s and 1990s, and their legacy infrastructure may not meet the technical standards required by SMRs. For example, the miniaturized design of SMRs may necessitate the construction of new dedicated transmission interfaces or alternative cooling technologies. Nonetheless, some elements—such as cleared land, grid connection points, or civil works—could still offer logistical and regulatory advantages in site selection and development. While this study does not quantify potential cost savings from infrastructure reuse, the international precedent reinforces the relevance of evaluating site-specific opportunities for optimizing SMRs deployment in Colombia.

Coal is one of the most carbon-intensive sources of electricity generation. According to the IPCC. (2014) AR5, pulverized coal combustion emits an average of 820 g CO_2eq per kWh, with a range between 740 and 910 g CO_2eq/kWh depending on plant efficiency and the coal type. In contrast, nuclear energy ranks among the lowest in life-cycle emissions. The 2022 UNECE report estimates that conventional nuclear power emits between 5.1 and 6.4 g CO_2eq/kWh (UNECE 2022). For SMRs, emissions vary on the basis of design. The NuScale SMR reports 4.6 g CO_2eq/kWh, whereas the Westinghouse AP300 is estimated at an average of 8.4 g CO_2eq/kWh, which still represents a drastic reduction compared with coal-fired generation (Carless et al., 2016).

The coal-to-nuclear approach offers not only a pathway to decarbonize Colombia's electricity sector but also an opportunity to enhance national energy security. International experience indicates that coal-to-nuclear conversions offer advantages in terms of supply stability, reduced infrastructure costs, and decreased dependence on fossil fuels (Li et al., 2024). In the case of Colombia, this strategy aligns with the country's nationally determined contribution (NDC) targets and with the long-term projections outlined in the National Energy Plan 2022–2052.

Historically, coal-fired electricity generation has been essential in Colombia's energy mix, but its share has progressively declined with the diversification of the sector (Oei and Mendelevitch 2018). Despite the country's decarbonization commitments and the growing integration of renewable sources, coal-fired thermal power plants still represent a significant portion of installed capacity. The oldest is PAIPA, which began operations in 1963 and consists of four units; the most recent unit was commissioned in 1999. ZIPAEMG began generation in 1964, and it also comprises four units, with the most recent having been added in 1985; like PAIPA, it is located in the central region of the country. In the northern region, GUAJIRA has been operating since 1983 and consists of two generation units (De la Pedraja Tomán 1985). TASAJERO, which is located in the northeastern region (Franco and Dyner 2018), and GECELCA, which is located in the northwestern region, began operations in 1985 and 2015, respectively (XM 2024).

The coal-to-nuclear strategy has environmental advantages that go beyond CO_2eq reduction, with the potential to enhance public health, especially in terms of air quality. The combustion of fossil fuels significantly contributes to premature mortality and pollution-related disease worldwide. Approximately 5.13 million excess deaths per year are attributable to ambient air pollution caused by fossil fuel use, representing 82% of all air pollution-related mortality (Lelieveld et al., 2023). A complete nuclear phase-out in the United States would result in approximately 5,200 additional premature deaths annually due to increased $PM_{2.5}$ and ozone exposure, with economic damage from health and climate impacts ranging between USD 51 billion and USD 220 billion yearly (Freese et al., 2023). Compared with fossil fuel-based generation, which produces high levels of NO_x and SO_2— precursors to fine particulate matter and tropospheric ozone—nuclear power plays a critical role in limiting air pollution and greenhouse gas emissions, especially (Thind et al., 2019; Mahmood et al., 2020). These pollutants are well-documented contributors to cardiopulmonary morbidity and mortality (Fowler et al., 2020).

In Colombia, public health and economic consequences are also significant. According to the National Planning Department (DNP), in 2018, more than 7,000 deaths were linked to PM2.5 exposure, resulting in an economic cost of COP 11.6 trillion—equivalent to 1.19% of national GDP, i.e., approximately USD 2.9 billion (DNP 2018). These figures emphasize the need for nonemitting, weather-independent baseload energy sources. SMRs provide such an option, offering continuous power generation without the air pollutant emissions associated with coal-fired plants (Vinoya et al., 2023). The deployment of SMRs could lead to substantial cobenefits in terms of decarbonization, improved air quality, reduced mortality, and long-term public health savings.

In addition to decarbonizing power generation, a coal-to-nuclear plan might substantially aid in reducing emissions in challenging sectors via cogeneration (Locatelli et al., 2015). As small modular reactors (SMRs) advance technologically and their implementation increases, their high-temperature heat and low-carbon electricity can be utilized for industrial applications, including ammonia synthesis, pink hydrogen production through high-efficiency electrolysis, and seawater desalination (IAEA 2023; Kim et al., 2023). These nonelectric applications, especially in areas with scarce freshwater resources or fossil fuel-reliant chemical industries, provide additional avenues for emission reduction (Buzzetti et al., 2024). The incorporation of SMRs into multiproduct energy systems could augment their total system value and broaden their contribution to achieving significant decarbonization across sectors beyond the electricity grid (Bicer and Dincer 2017).

4 Methodology

This study utilized two complementary approaches to estimate the cumulative reduction in CO_2eq emissions resulting from a progressive coal-to-nuclear substitution strategy using SMRs in Colombia between 2035 and 2052. First, a deterministic model was developed to calculate annual avoided emissions on the basis of installed capacities, capacity factors, the decommissioning schedules for existing coal plants, and average emission factors. To account for uncertainty in the technical parameters, a Monte Carlo simulation was subsequently implemented. This probabilistic model estimates a distribution of possible outcomes by randomly varying emission factors within plausible ranges across 10,000 iterations. Together, these two approaches provide a more robust and reliable assessment of the mitigation potential associated with this energy transition strategy. It is important to note that both modeling approaches assume a fixed, uninterrupted deployment of SMRs beginning in 2035. This schedule does not account for potential delays in licensing, construction, or fuel supply. As such, the results represent an idealized decarbonization pathway based on optimistic planning conditions, consistent with exploratory scenarios used in long-term energy system analyses. This approach is consistent with long-term scenario analysis practices used by international energy planning agencies (e.g., IEA, IRENA), which rely on assumed timelines to assess strategic potential rather than short-term operational certainty (IEA, 2021; IRENA USAID., 2021). These assumptions are acknowledged as a limitation of the study and are addressed in the discussion section.

4.1 Deterministic model

The analysis is based on the high-end energy transition scenario outlined in Colombia's National Energy Plan (PEN) 2022–2052, which projects a total installed capacity of 1771 MW of electricity generation still coming from coal. The modeling framework is built based on an emission reduction equation, defined as the difference between the emissions in a reference scenario, in which coal-fired power plants continue operating according to PEN projections, and a transition scenario, in which these plants are gradually replaced by small modular nuclear reactors (SMRs). This study established a decommissioning schedule for Colombia's coal-fired thermal power plants on the basis of their operational age and the criterion that they operate under dispatch to the National Interconnected System. The scheduled retirement years are presented in Table 1.

New nuclear generation capacity is introduced in a phased approach, starting in 2035 with the deployment of 6 SMRs, each with an installed capacity of 300 MW. Installed capacity increases progressively until the full replacement of coal is achieved by 2051. The impact on the emission reduction pathway is modeled using energy balance equations and emission conversion factors, considering the CO_2eq intensity per kWh for each technology. The analysis evaluates both annual and cumulative emission trajectories over the study period and compares the outcomes of the reference scenario, where coal-fired plants remain operational in accordance with the PEN 2022–2052, with those of the coal-to-nuclear transition scenario.

This approach makes it possible to identify key inflection points in the emission trajectory and to quantify the climate mitigation effect of gradual coal-to-nuclear substitution. The methodology is grounded in official data from the Colombian Mining and Energy Planning Unit (UPME), as well as international studies on coal-to-nuclear conversion impacts, ensuring both analytical robustness and contextual relevance for Colombia's energy transition.

CO_2eq emission reductions are modeled as the difference between the business-as-usual (BAU) scenario and the coal-to-nuclear energy transition scenario. The emission reduction pathway is defined as shown:

$$E_{avoided,t} = E_{BAU,t} - E_{nuclear,t}$$

where $E_{avoided,t}$ denotes the emissions mitigated in year t, $E_{BAU,t}$ corresponds to the emissions under the business-as- usual scenario with no intervention, and $E_{nuclear,t}$ refers to the emissions generated under the coal-to-nuclear transition scenario. To determine $E_{BAU,t}$, the annual energy generation from coal is calculated on the basis of

TABLE 1 Coal-fired power plants in Colombia and suggested decommissioning dates.

Coal-fired power plant	Units	Capacity (MW)	Commissioning date	Decommissioning date
PAIPA	4	373	1963	2035
ZIPAEMG	4	227	1964	2039
GUAJIRA	2	324	1983	2043
TASAJERO	2	356	1985	2047
GECELCA 3	2	491	2015	2051

Notes: PAIPA, termopaipa; ZIPAEMG, Central Termoeléctrica Zipa–Empresa de Energía de Bogotá; GUAJIRA, termoguajira; TASAJERO, termotasajero; GECELCA, 3 = Central Termoeléctrica Gecelca 3 – Generadora y Comercializadora de Energía del Caribe S.A.S. E.S.P.
Data from XM, 2024.

the projected installed capacity and the capacity factor of the coal-fired power plants. The electricity generation in GWh is given by:

$$G_{coal,t} = C_{coal,t} \times H \times CF_{coal}$$

where $G_{coal,t}$ is the annual electricity generation from coal in year t, $C_{coal,t}$ is the installed capacity in MW, H represents the number of hours in a year (8,760 h/year), and CF_{coal} is the capacity factor of coal-fired power plants, which is assumed to be 65% (IEA 2024). On the basis of the estimated coal generation, CO_2eq emissions under the BAU scenario are calculated as follows:

$$E_{BAU,t} = G_{coal,t} \times EF_{coal}$$

where EF_{coal} is the emission factor of coal, which is assumed to be 935 gCO_2eq/kWh, within a broader range of 820 (IPCC, 2014) to 1,050 gCO_2eq/kWh as reported by the Whitaker et al. (2012) and extended in subsequent life-cycle assessment literature. This selection is consistent with the methodology used by Colombia's National Inventory of Atmospheric Emissions and Absorptions (IDEAM), which applies IPCC default values in the absence of nationally measured emission factors for coal combustion (Mads and Pnud, 2025). In Colombia, most coal used in thermal generation corresponds to high-volatile lignite or bituminous coal, which are associated with higher specific emissions due to their lower calorific value and combustion efficiency. Although no official disaggregated emission coefficients have yet been published for domestic use, the upper bound of the IPCC range (1,050 gCO_2eq/kWh) is appropriate for conservative modeling purposes in the Colombian context, providing a scientifically valid estimate until more detailed local measurements become available.

In the transition scenario, the electricity generation that replaces coal is assumed to come from SMRs, and it is calculated using the following equation:

$$G_{\text{nuclear},t} = C_{SMR,t} \times H \times CF_{SMR}$$

where $G_{nuclear,t}$ is the electricity generation from SMRs in year t, $C_{SMR,t}$ is the installed capacity of small modular reactors, and CF_{SMR} is their capacity factor, which is assumed to be 95%. This value corresponds to the upper bound identified in the systematic review by Mignacca and Locatelli (2020), which examined performance expectations across a range of SMRs technologies in both commercial and pre-commercial phases. Emissions under the coal-to-nuclear strategy are calculated as follows:

$$E_{\text{nuclear},t} = G_{\text{nuclear},t} \times EF_{\text{nuclear}}$$

where $EF_{nuclear}$ represents the life-cycle emission factor of nuclear electricity generation, expressed in gCO_2eq/kWh.

The emission factor used for SMRs (6.5 gCO_2eq/kWh) is based on a simple arithmetic average of the two most comprehensive and publicly available life-cycle assessments (LCA) for small modular reactors: the NuScale design (4.6 gCO_2eq/kWh) and the Westinghouse AP300 (8.4 gCO_2eq/kWh), as reported by UNECE (2022) and Carless et al. (2016). These values include emissions from the full life cycle of each technology, encompassing construction, operation, fuel processing, and decommissioning stages. The use of this average value allows for a conservative yet realistic approximation of SMR performance in the absence of a final technology selection for Colombia. This parameterization ensures compatibility with IPCC standards for life-cycle comparison across electricity generation technologies. The cumulative reduction in CO_2eq emissions over the transition period is obtained by summing the annual reductions:

$$E_{\text{avoided,cumulative}} = \sum_{t=2035}^{2052} E_{\text{avoided},t}$$

This approach makes it possible to assess the decarbonization trajectory and allows the emission trends between the coal continuity scenario and the nuclear transition scenario to be compared.

4.2 Monte Carlo Simulation

The primary sources of uncertainty in the simulation include the coal and SMR emission factors and the installed thermal generation capacity projected for 2052. For these variables, the ranges defined in the deterministic model were used. The capacity factor of small modular reactors is represented by a triangular distribution ranging from 85% to 95%, with a most likely value of 93%, which is in line with performance data from operating and planned reactors (Zohuri and McDaniel, 2020; Abou-Jaoude et al., 2024).

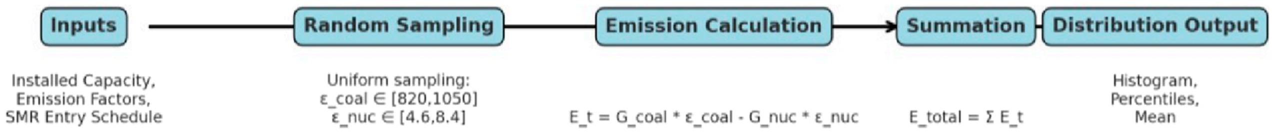

FIGURE 1
Simulation flow for uncertainty analysis of CO_2 emissions avoided.

The thermal generation capacity projected for 2052—estimated at 1771 MW in the upper-bound scenario of the PEN 2022–2052—is also modeled using a uniform distribution, reflecting uncertainty regarding early retirement policies or potential life extensions of coal plants (see Figure 1).

The distribution of simulation outcomes is analyzed using descriptive statistics, with a percentile-based interpretation to characterize optimistic, conservative, and pessimistic scenarios in terms of emission reductions. Additionally, a sensitivity analysis is conducted to identify which variables most influence the variability of the results and to assess the robustness of the projected energy transition. This methodology offers a more accurate view of the climate benefits of coal-to-nuclear substitution by incorporating realistic scenarios and the inherent uncertainty of operational parameters in Colombia's energy system.

5 Results

Deterministic analysis of the temporal trajectory of emission reductions shows that the cumulative impact of replacing coal-fired generation with nuclear reactors is progressive and accelerates as the transition progresses. In 2036, avoided emissions reach approximately 14.78 $MtCO_2eq$, reflecting the retirement of the PAIPA power plant. Between 2040 and 2044, annual reductions range from 41.94 to 63.28 $MtCO_2eq$ due to the phase-out of ZIPAEMG and GUAJIRA. By 2052, cumulative avoided emissions reach 82.62 $MtCO_2eq$ following the retirement of TASAJERO and GESELCA. These results indicate that the coal-to-nuclear transition enables deep decarbonization of the power sector, ensuring sustained emission reductions and supporting Colombia's compliance with its climate commitments (see Figure 2).

The Monte Carlo simulation enabled the assessment of uncertainty in CO_2eq emission reductions under the coal-to- SMR substitution strategy. Probability distributions were applied to the emission factors of coal and nuclear technologies, the capacity factor of SMRs, and the total installed thermal capacity to be replaced. This simulation reveals a robust and consistent outcome regarding the cumulative CO_2 emissions avoided through the coal-to- nuclear strategy in Colombia between 2035 and 2052. The mean value of avoided emissions is 76.2 $MtCO_2eq$, with a median (P50) that is nearly identical at 76.3 $MtCO_2eq$, indicating a symmetric and stable distribution. The standard deviation is 6.58 $MtCO_2eq$, representing approximately 8.6% of the mean, which suggests moderate variability in response to uncertainty in input parameters such as emission factors and capacity factors. This level of dispersion is statistically reasonable for energy system modeling, demonstrating that the core findings remain consistent even when key technical assumptions are varied. Furthermore, the 5th and 95th percentiles (P5 and P95) are 66.2 $MtCO_2eq$ and 86.4 $MtCO_2eq$, respectively, delineating a 90% confidence interval of approximately ±13 $MtCO_2eq$ around the central estimate. These results reinforce the reliability of the coal-to-nuclear transition scenario and highlight the resilience of the model under plausible uncertainty conditions (see Figure 3).

The deterministic model produces a cumulative avoided emissions estimate of 82.62 $MtCO_2eq$, whereas the median value derived from the Monte Carlo simulation is 76.04 $MtCO_2eq$. This discrepancy reveals that the deterministic approach, which is based on fixed input assumptions, slightly overestimates the central tendency of emissions reductions when real-world uncertainty is considered. The relative deviation—approximately 8%—is statistically significant and illustrates how deterministic models may provide optimistic outcomes under static assumptions. In contrast, the Monte Carlo framework accounts for the inherent variability in key technical parameters, such as emission intensity and capacity factors, yielding a probabilistic distribution of outcomes that reflects a broader range of plausible operational scenarios.

The sensitivity analysis reveals that avoided emissions in the coal-to-nuclear scenario are strongly influenced by the emission factor of coal, with a correlation coefficient of 0.86. This finding implies that in countries where coal-based generation has high carbon intensity, replacing it with small modular reactors (SMRs) will exert a greater impact on climate change mitigation. In the case of Colombia, where the emission factor for coal ranges from 820 to 1,050 g of CO_2eq per kWh, the uncertainty in this parameter largely determines the variability of the Monte Carlo simulation results. The capacity factor of SMRs also plays a key role in emission reductions, with a correlation coefficient of 0.51. This result suggests that the greater availability and operational efficiency of reactors significantly contribute to power sector decarbonization. Conversely, the emission factor range for SMRs (4.6–8.4 gCO_2eq/kWh) shows a low negative correlation of −0.06. This finding indicates that although nuclear energy has a substantially lower carbon footprint than coal does, the variability within that low range has a limited influence on total CO_2eq reductions. Overall, these results highlight the importance of reducing coal dependency in the power sector and optimizing SMR operation to maximize the contribution of SMRs to Colombia's decarbonization efforts (see Figure 4).

6 Discussion

The transition from coal-based electricity generation to SMRs represents not only an opportunity to decarbonize the

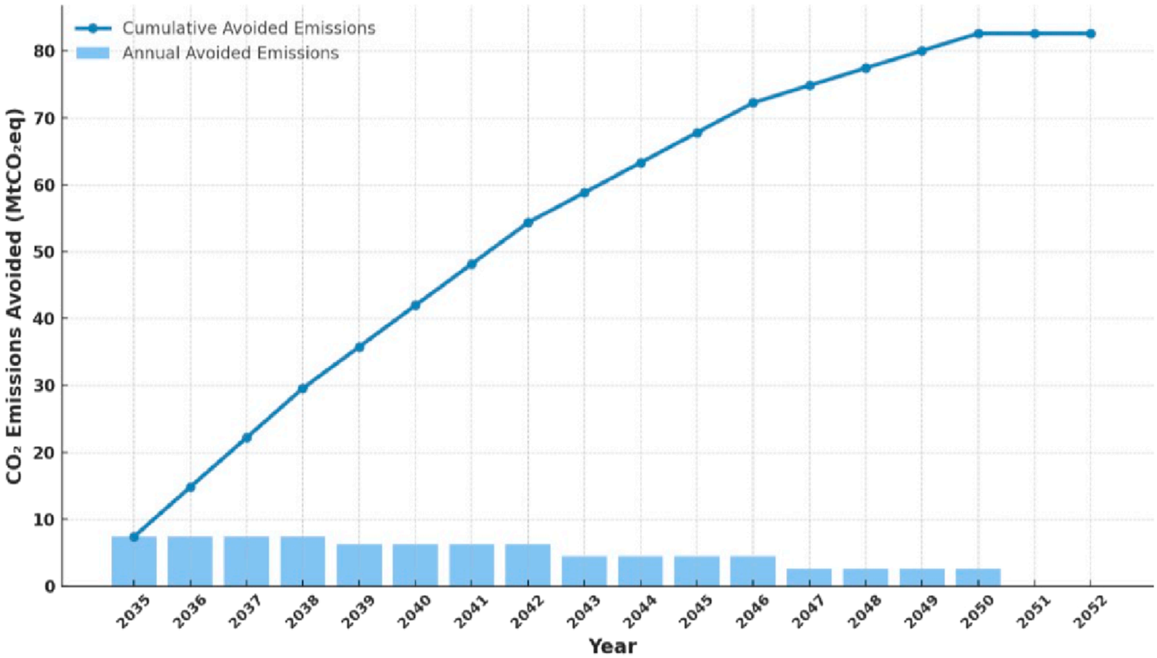

FIGURE 2
Trajectory of CO_2 emissions avoided in Colombia (2035–2052).

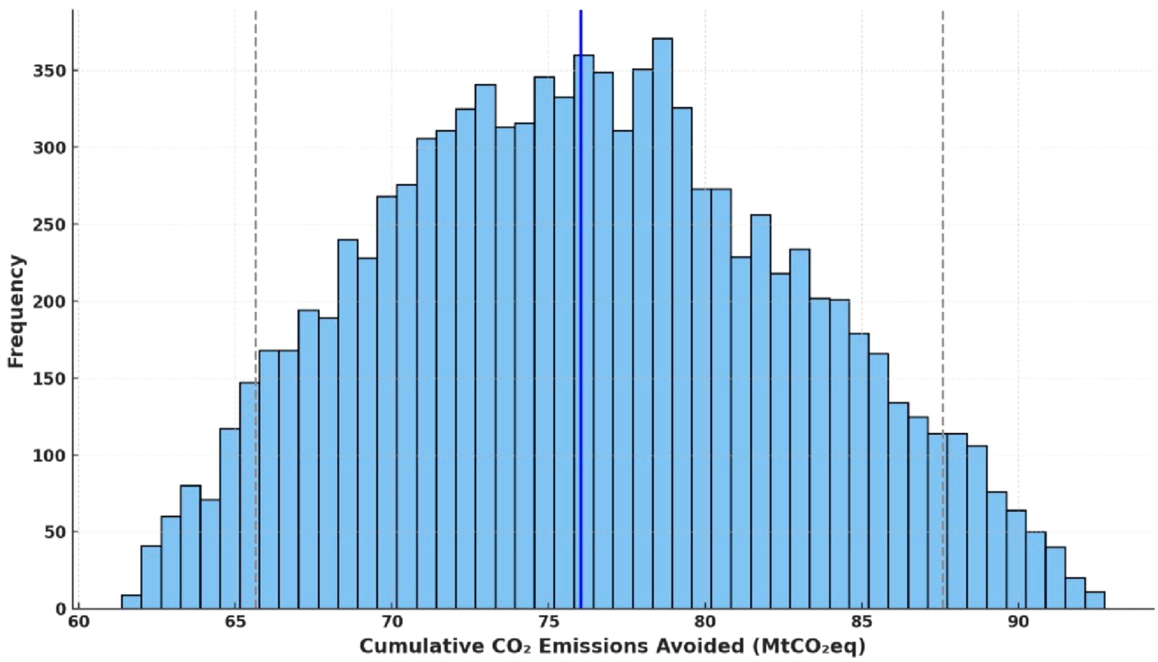

FIGURE 3
Monte Carlo simulation–cumulative avoided CO_2 emissions (2038–2052)

energy sector but also a pathway for improving air quality and public health. Coal-fired power plants are significant sources of atmospheric pollutants such as particulate matter, sulfur oxides, and nitrogen oxides, all of which contribute to air quality degradation and are linked to respiratory and cardiovascular diseases. In Colombia, where elevated levels of air pollution persist in areas surrounding thermal power complexes, the progressive decommissioning of these plants would reduce the incidence of pollution-related illnesses and alleviate the burden on the public health system.

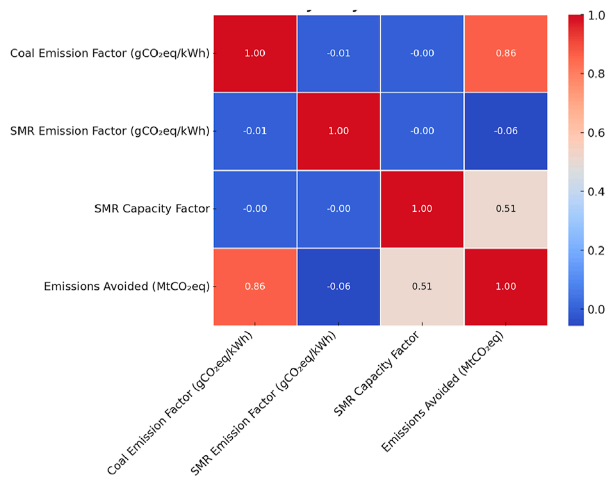

FIGURE 4
Sensitivity analysis: Correlation matrix.

In addition to reducing CO_2eq emissions and improving air quality, the deployment of SMRs addresses a structural challenge in Colombia's electricity system. Hydropower has historically dominated the country's electricity supply, accounting for more than 65% of the energy matrix. However, its high variability—driven by extreme climate events such as El Niño—has led to several energy crises, including a major crisis in 1992 (IRENA, 2021a). Diversifying the energy mix with a reliable baseload source such as nuclear power, which is characterized by a high-capacity factor, would mitigate the vulnerability of the system to prolonged droughts. This is particularly relevant for SMRs that are not water cooled. Among these prototypes are those cooled by gas, lead molten salt or sodium (Serp et al., 2014; Fernández-Arias et al., 2024).

In order to assess the real-world applicability of the coal-to-nuclear transition strategy in Colombia, a preliminary site suitability analysis was conducted based on the locations of existing coal-fired power plants. Table 2 presents a comparative evaluation using criteria derived from IAEA guidelines (e.g., SSG-35), including seismic zoning, availability of water resources (for cooling purposes), and proximity to high-voltage transmission infrastructure. Results indicate that most of the targeted sites—particularly PAIPA, GUAJIRA, and GECELCA three—exhibit favorable conditions for the deployment of SMRs, both in terms of geophysical stability and infrastructural readiness. Locations such as ZIPAEMG and TASAJERO, which are situated in areas with moderate to high seismicity, may still be suitable depending on the reactor technology selected, especially if water-independent cooling systems (e.g., gas, sodium, or molten salt) are used. This analysis suggests that Colombia has a geographically diverse but technically viable set of candidate sites, reinforcing the strategic feasibility of a coal-to-SMR transition if siting challenges are properly addressed through detailed feasibility assessments.

This study focuses on the coal-to-nuclear replacement pathway, in alignment with Colombia's National Energy Plan (PEN 2022–2052), which includes the potential deployment of small modular reactors (SMRs) as a firm low-carbon alternative to retiring coal-fired capacity. While other transition strategies—such as coal-to-renewables (e.g., solar PV or wind combined with storage) or retrofitting coal with carbon capture and storage (CCUS)—are important for the broader energy transition, their direct comparison falls outside the scope of this paper. Nevertheless, to provide context, we draw on internationally recognized levelized cost of electricity (LCOE) benchmarks. Specifically, the LCOE for SMRs is based on the meta-analysis conducted by the Idaho National Laboratory (Abou-Jaoude et al., 2024), which estimates a moderate-case LCOE of 88 USD/MWh by 2030, with a sensitivity range from 134 USD/MWh (pessimistic) to 53 USD/MWh (optimistic). At the time of this analysis, the Colombian Mining and Energy Planning Unit (UPME) was in the process of updating its methodology for estimating standardized LCOE values across technologies. In contrast, international medians for solar PV and onshore wind range from 56 to 50 USD/MWh, respectively, while coal and combined-cycle gas are reported at 88 and 71 USD/MWh under similar assumptions (IEA/NEA, 2020).

Importantly, this study does not model a specific SMR design. Instead, it employs generalized performance parameters derived from the literature on current design candidates, enabling results to be interpreted flexibly across different regulatory and technological pathways. Although this study does not model a specific SMR design, the results are informed by representative parameters of leading reactor classes currently in advanced stages of development. Among these, several SMR technologies have distinct technical requirements and advantages that make them more or less suitable for deployment in specific national contexts. For example, pressurized water reactors (PWR), such as the NuScale and AP300 designs, are among the most mature technologies and have well-established regulatory frameworks, but typically require abundant water resources for cooling. This may limit their deployment in arid or water-stressed regions, such as the Caribbean coast or certain areas of the Andean interior. In contrast, molten salt reactors (MSRs) or sodium-cooled fast reactors (SFRs) offer greater flexibility in siting due to their higher thermal efficiency, passive safety features, and reduced dependence on water cooling. These designs may be particularly advantageous for Colombia, where hydrological variability due to El Niño–Southern Oscillation (ENSO) events and increasing water stress in some river basins could constrain traditional cooling options. Additionally, air-cooled high-temperature gas reactors (HTGRs) could allow deployment in remote or industrial zones where water access is limited or where coupling with industrial heat applications is desired. (see Table 3).

Therefore, even though a single prototype has not been selected for Colombia, the comparative suitability of different SMR classes can inform future planning and pre-feasibility studies. Future work should integrate site-specific constraints, including water availability, seismic zoning, grid connectivity, and proximity to demand centers, to refine the technological match between SMR types and potential locations. This generic approach supports scenario-level analysis, but future work should refine these assumptions using design-specific data on investment cost, deployment timelines, and technical siting conditions for Colombia (Kindra et al., 2024).

Beyond LCOE considerations, SMRs offer distinct advantages in terms of system-level integration. Unlike variable renewable energy

TABLE 2 Preliminary site suitability assessment for SMR deployment in Colombia.

Coal-fired plant	Location (Dept., Municipality)	Seismic zoning (SGC)	Water source availability	Proximity to HV grid	Preliminary suitability for SMRs
PAIPA	Boyacá, Paipa	Low–Moderate	Lake Sochagota & Chicamocha River	Yes (Paipa substation nearby)	High (all criteria favorable)
ZIPAEMG	Cundinamarca, Zipaquirá	Moderate	Neusa and Tominé Reservoirs (proximity)	Yes (ZIPA substation)	Moderate (sismicity higher, but manageable)
GUAJIRA	La Guajira, Albania	Low	Ranchería river basin	Yes (interconnection with Cerrejón)	High (low sismicity and available water)
TASAJERO	Norte de Santander, San Cayetano	Moderate–High	Zulia river basin	Yes (Sistema Nororiental)	Moderate (needs cooling tech not water-dependent)
GECELCA 3	Córdoba, Montería	Low–Moderate	Sinú River	Yes (Cerromatoso grid zone)	High (low seismicity, grid and water available)

Notes: Preliminary site suitability assessment for SMR, deployment in Colombia based on current coal-fired power plant locations. The evaluation considers seismic zoning (based on Servicio Geológico Colombiano SGC, data), water availability for cooling (if required), and proximity to high-voltage grid infrastructure.

TABLE 3 Technological suitability of SMR classes for Colombia.

SMR type	Reactor coolant	Cooling requirement	Technological maturity	Contextual suitability in Colombia
Pressurized water reactor (PWR)	Water	High	High (e.g., NuScale, AP300)	Suitable in water-abundant regions with regulatory infrastructure
Molten salt reactor (MSR)	Liquid salt	Low	Medium (pre-commercial prototypes)	Suitable in water-stressed areas or with ENSO vulnerability
Sodium-cooled fast reactor (SFR)	Liquid sodium	Low	Medium (demonstration stage)	Adaptable to remote zones with limited hydrology
High-temperature gas reactor (HTGR)	Helium	Very Low (air-cooled)	Medium–High (e.g., X-Energy, HTR-PM)	Ideal for coupling with industrial heat; limited by cost and scale

Note: Preliminary comparison of small modular reactor (SMR) types in terms of technological maturity, cooling requirements, and contextual suitability for deployment in Colombia. This assessment is based on publicly available characteristics of advanced SMR, designs and Colombian geoclimatic conditions. Technical data from IAEA (2025).

(VRE) sources such as wind and solar, which are inherently weather-dependent and require firming capacity from storage or flexible thermal units (Zhang et al., 2023), SMRs provide uninterrupted, dispatchable power with high capacity factors—often exceeding 90%—and contribute synchronous inertia to the grid. These features make SMRs a strategic enabler of deeper renewable integration while preserving system reliability (Singh and Alam, 2024). In Colombia's context, where increasing VRE penetration is expected, SMRs can act not as substitutes but as complementary assets that stabilize the energy matrix. While CCUS remains a promising pathway, its cost-competitiveness depends on high carbon prices (above 60 USD/tCO_2), which are not currently in place in the Colombian market (IEA/NEA, 2020). As such, future studies should expand the comparative assessment across multiple decarbonization routes, including nuclear, VRE, storage, and CCUS, using system-wide cost-effectiveness and emissions metrics.

While this study focuses on avoided CO_2 emissions, it is important to acknowledge that SMRs also generate spent nuclear fuel and radioactive waste. Colombia currently adheres to international safety frameworks and has adopted national regulations such as Resolution 40,234 of 2024, which establishes technical criteria for the safe management of radioactive waste. However, broader deployment of nuclear technologies will require the consolidation of a comprehensive regulatory and institutional framework for long-term storage and disposal, in line with IAEA standards (e.g., GSR Part 5) and OECD-NEA guidance (MME, 2024). Advances in fuel cycle technologies, including MOX and REMIX, offer pathways to reduce both the volume and radiotoxicity of high-level waste through the reuse of spent fuel. Although not yet widely deployed in SMRs, these approaches could enhance sustainability in future reactor generations. Moreover, SMRs emit no conventional air pollutants such as SO_2, NO_x, or $PM_{2.5}$, positioning them as environmentally advantageous compared to coal-based generation. Therefore, while nuclear waste requires rigorous oversight, the overall environmental footprint of SMRs remains significantly lower than that of fossil alternatives.

From a strategic perspective, adopting SMRs in Colombia would contribute not only to reducing greenhouse gas and pollutant emissions but also to strengthening the resilience of the electricity system in the context of climate change and increasing energy demand. Additionally, investment in this technology could position Colombia at the forefront of the energy transition in Latin America, facilitating the integration of innovative solutions and fostering international cooperation in the development of the nuclear sector. However, the success of this strategy will depend on the formulation of appropriate policies, the public's acceptance of nuclear energy, and the establishment of regulatory mechanisms that ensure the safe and viable deployment of these technologies in the country.

While conventional nuclear reactors often require more than 10 years from planning to operation, the modular nature of SMRs is expected to reduce construction timelines. Literature suggests that first-of-a-kind (FOAK) SMRs may still require between 7 and 10 years, but subsequent units could benefit from standardization and modular fabrication, potentially reducing deployment times to 3–5 years once regulatory frameworks are established and supply chains are matured (Abou-Jaoude et al., 2024; Mignacca and Locatelli 2020).

7 Conclusion

This study quantifies the climate impact of a coal-to-nuclear strategy in Colombia, demonstrating that the progressive replacement of coal-fired thermal generation with SMRs between 2035 and 2052 could avoid cumulative emissions of approximately 76.04 $MtCO_2eq$. Using both a deterministic and a stochastic modeling approach, the results provide robust estimates of emission reductions and reveal that uncertainty in key technical parameters—such as coal emission intensity and reactor capacity factors—has a significant influence on outcomes. The findings underscore the importance of integrating probabilistic frameworks into long-term energy planning to avoid overestimating mitigation potential.

Beyond its quantitative results, the study also highlights broader considerations essential for the viability of SMRs in Colombia. First, while the model assumes an idealized deployment timeline, it acknowledges real-world constraints such as licensing, construction timelines, site suitability, and infrastructure readiness. A geographic assessment of existing coal plant sites confirms that several locations meet the technical criteria for potential SMR deployment.

Second, although this analysis does not model alternative decarbonization scenarios in detail, it includes a comparative discussion of LCOE estimates from international sources. These comparisons suggest that SMRs could play a complementary role alongside renewables, particularly as a firm, low-emission source of electricity to support grid stability and resilience in the face of hydropower variability.

Third, the study recognizes the environmental trade-offs associated with nuclear technology. While SMRs do not emit CO_2 or air pollutants such as SO_2 or NO_x, they generate radioactive waste that must be safely managed. Colombia has adopted a regulatory framework (Resolution 40,234 of 2024), and future deployments will require its continued development. Emerging fuel cycle innovations such as MOX and REMIX offer promising pathways for reducing long-term waste volumes and toxicity.

Considering these findings, the coal-to-nuclear pathway represents a technically and environmentally viable strategy for decarbonizing Colombia's electricity system. Its success, however, will depend not only on emissions performance but also on technological selection, regulatory readiness, site-specific feasibility, and social acceptance. The methodology and findings presented here may serve as a reference for other countries facing similar challenges in aligning climate goals with reliable energy access.

8 Recommendations for future research

In future research, it is essential to advance the development of a national regulatory framework that enables the evaluation and potential deployment of SMRs in Colombia. In this context, the technical and regulatory guidance of the IAEA will be crucial in designing a roadmap tailored to the country's specific conditions. Future work should also incorporate dynamic deployment scenarios that reflect regulatory delays, construction timelines, and infrastructure readiness. Developing sensitivity analyses that include lagged deployment or partial fulfillment of nuclear capacity targets would offer more comprehensive insights into the feasibility and impact of SMRs under real-world constraints. Integrating site suitability metrics (e.g., seismic zoning, water availability, grid proximity) into spatially explicit modeling would further enhance decision-making for SMR siting and policy design.

Moreover, it would be relevant to explore how nonelectric applications of SMRs—such as pink hydrogen production, ammonia synthesis, industrial process heat supply, and desalination—could significantly contribute to further emission reductions, thus expanding the impact of these technologies within the broader scope of Colombia's energy transition.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CP: Writing – original draft, Investigation, Writing – review and editing. DP: Formal Analysis, Data curation, Methodology, Writing – review and editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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