Past, present and future of nuclear energy in Colombia from the deployment of SMALL MODULAR REACTOR

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**Abstract**

This paper explores the trajectory of nuclear energy in Colombia within the context of its development in Latin America, emphasizing the deployment of Small Modular Reactors. It examines the socio-economic, political, and technological factors that have historically influenced regional nuclear energy adoption, discussing the potential for SMRs to diversify Colombia's energy matrix. This discussion extends to analyzing the strategic advantages and challenges of nuclear energy, underlining its role in sustainable development and carbon free emissions.

## INTRODUCTION

Nuclear energy is at a critical juncture in its global development, recognized for its ability to generate significant electricity with minimal carbon emissions, making it a crucial part of energy strategies in developed countries as a stable, reliable alternative to inconsistent and environmentally harmful fossil fuels. However, its adoption in Latin America remains in its nascent stages, facing unique regional challenges and possessing considerable untapped potential. In contrast to regions like Europe or North America where nuclear power is integral for energy security and environmental goals, Latin America's energy mix has been modest in nuclear energy, primarily due to historical, economic, and political factors, with a traditional reliance on more accessible resources like hydrocarbons and hydroelectric power. Key barriers to nuclear energy adoption in the region include the high initial costs of nuclear plants, public safety concerns from global nuclear incidents, a lack of regional nuclear expertise, and the political and economic instability that complicates securing investments and sustaining long-term nuclear projects.

Despite the challenges, there are significant opportunities for nuclear energy in Latin America, particularly as a reliable complement to intermittent renewable sources like solar and wind. This is especially relevant in countries like Colombia, where climate-induced variability threatens the reliability of hydroelectric power. SMRs offer a more adaptable and cost-effective nuclear solution, well-suited to Colombia unique geographic and economic conditions. This approach could diversify the energy matrix, decrease reliance on traditional energy sources, and significantly reduce greenhouse gas emissions.

This paper will explore in depth how Colombia can progress towards integrating nuclear energy, focusing on strategic planning, technological innovation, and policy frameworks. It will also consider critical aspects of safety and public acceptance, ensuring that the transition to nuclear energy is not only technologically robust but also socially responsible and environmentally sustainable.

## Nuclear Energy Context in Latin America

Nuclear power's share in Latin America remains notably low, accounting for only 2.2% of the region's total electricity generation [1]. This minimal integration can be attributed to various regional-specific challenges, including disparities in infrastructure, policy, and technological adoption, as summarized below [2]:

* **Infrastructure Limitations:** Many Latin American countries lack the industrial base and specialized infrastructure required to develop and maintain nuclear power plants. This includes not only the physical infrastructure but also the regulatory and safety frameworks.
* **Economic and Policy Barriers:** Nuclear power requires significant upfront investment, which can be a deterrent for economies with limited financial resources and do not align well with the political and economic instability that some countries in the region experience.
* **Public Perception and Historical Context:** The public's perception of nuclear energy in Latin America has been influenced by global nuclear accidents and a general lack of awareness about the safety advancements in modern nuclear technology.

Despite these challenges, there are notable exceptions in the region:

* **Argentina:** As a pioneer in nuclear technology in Latin America, Argentina operates three nuclear reactors and has a fourth under construction. The country has a comprehensive nuclear policy framework, supported by a strong educational and technological infrastructure, which includes indigenous uranium enrichment capabilities and fuel fabrication. Argentina's nuclear program, initiated in the 1950s, reflects a longstanding commitment to nuclear energy as part of its national energy strategy [3].
* **Brazil:** Brazil is home to the largest nuclear power plant in Latin America, the Angra facility, which includes two operational reactors and a third under construction. Nuclear energy in Brazil contributes to about 2.4% of the electricity mix, with plans to expand this capacity to meet the country's increasing energy demands while reducing dependence on hydroelectric power, which is vulnerable to fluctuating weather patterns and climate change [4] Recent plans indicate further development in this sector, aimed at enhancing capacity and addressing energy security and climate change mitigation [5].
* **Mexico:** Mexico has one nuclear power plant, Laguna Verde, with two operational reactors. While nuclear energy makes up a small fraction of Mexico's overall energy mix, it represents a critical component of the country's strategy to diversify its energy sources and reduce its reliance on fossil fuels [6].

## THE POTENTIAL AND CHALLENGES FOR NUCLEAR ENERGY IN COLOMBIA

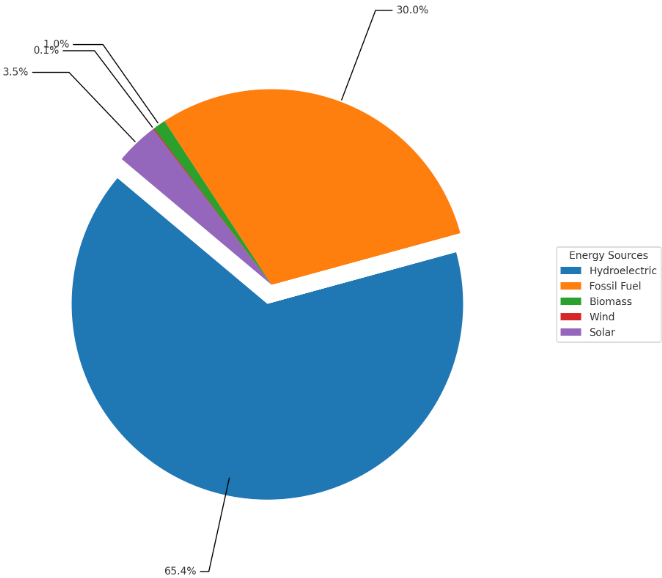
The IAN-R1, Colombia’s sole nuclear research reactor, was commissioned in 1965 during the presidency of Guillermo León Valencia. This facility was donated by the United States as part of the Atoms for Peace program, aimed at promoting the peaceful use of atomic energy. Since its establishment, the reactor has supported scientific research contributing to sectors such as agriculture, health, geology, and industry.

Concurrently, Colombia endured a prolonged armed conflict from 1964 to 2016, which inflicted significant economic costs estimated at approximately 178 billion dollars. A considerable portion of this expenditure, sourced from taxpayer money, could have otherwise been allocated to advancing energy technologies, education, and healthcare services [7]. The conflict concluded with the signing of a peace agreement by then-President Juan Manuel Santos and the FARC-EP on September 26, 2016, an event that also earned Santos the Nobel Peace Prize.

In the post-conflict period, it is imperative for Colombia to prioritize enhancing energy access, securing energy stability, and developing expertise in new nuclear technologies. These efforts are critical to achieving the national goal of zero emissions by 2050.

Colombia's energy sector, predominantly powered by hydroelectricity, faces a unique blend of opportunities and challenges, the introduction of nuclear energy into Colombia's energy matrix would require significant infrastructure investments, development of specialized human capital, and robust public engagement on nuclear safety and viability. This comprehensive approach would necessitate careful consideration of regulatory frameworks, technological readiness, and socio-economic impacts.

The pie chart depicted in Figure 1 illustrates the distribution of energy generation by source in megawatts (MW) across various technologies in Colombia. Hydroelectric power dominates the energy mix, contributing most of the total output, followed by fossil fuels. Other renewable sources such as biomass, wind, and solar, although smaller in scale, play a crucial role in diversifying the energy portfolio and reducing dependency on non-renewable sources.



*Fig. 1. Effective installed capacity (MW) in Colombia as of April 2024. Source [8], own elaboration.*

Hydroelectric power makes Colombia's energy grid vulnerable to climate variability. During periods of drought, which can be exacerbated by El Niño phenomena, water scarcity directly impacts hydroelectric production, posing risks to energy security and economic stability. Nuclear energy offers a reliable and consistent output that is not subject to these environmental variables, providing a stable base-load energy source that could significantly enhance Colombia's energy security.

In alignment with Colombia's obligations under COP28, the nation has set forth ambitious objectives to diminish its greenhouse gas emissions [9]. The National Council for Economic and Social Policy promulgated the Energy Transition Policy document "CONPES 4075 of 2022" [13]. This policy delineates four strategic axes designed to: enhance energy security; foster knowledge and innovation within the energy transition; boost competitiveness and economic development through the energy sector; and cultivate a low-carbon energy system to mitigate climate change effects.

Specifically concerning nuclear energy, the policy outlines two pivotal commitments. The first is to assess the potential role of nuclear power as a viable technology within the country's energy transformation. The second commitment involves conducting a pre-feasibility analysis to guide Colombia's decision-making regarding the adoption of nuclear power.

To illustrate the distinctions and synergistic potential between the existing hydroelectric power infrastructure and proposed nuclear solutions through SMRs, the Table 1 provides a comparative overview. This comparison highlights key aspects such as energy stability, environmental impact, and economic considerations, which are crucial for understanding the strategic positioning of these technologies within Colombia's energy matrix.

Table 1. Comparison of status between hydroelectricity and SMR in Colombia

| Feature | Hydroelectric Power | SMRs |
| --- | --- | --- |
| Energy Stability | Subject to climatic variability; can be unreliable in droughts. | Provides stable base-load power; not affected by weather. |
| Capital Investment | High initial costs; dependent on geographical conditions. | Lower initial capital compared to traditional reactors; scalable investments. |
| Environmental Impact | Low carbon emissions but can impact water ecosystems and biodiversity in flooding zones. | Minimal land usage; no emissions during operation. |
| Infrastructure Needs | Requires large-scale structures and significant land areas. | Smaller footprint; can be integrated into existing grids more easily. |
| Public Perception | Generally positive, known technology. | Requires careful security and safety management due to safety concerns and misconceptions. |
| Regulatory Requirements | Well-established regulatory frameworks. | Needs development of new regulations and safety protocols. |
| Flexibility | Limited flexibility: output depends on water availability. | High flexibility; can be deployed in various settings including remote areas. |
| Economic Development | Contributes to local economies, but mainly during construction. | Potential for ongoing economic benefits through technology, education, and research development. |

Integrating nuclear power in Colombia involves significant challenges such as high upfront investments in construction, safety systems, and waste management, and the necessity for securing funding and financial stability. Developing a skilled workforce in nuclear engineering, safety protocols, and operational management is essential, possibly through educational programs and international partnerships.

Within the academic sphere and through independent initiatives, several Colombian universities have actively promoted education on nuclear issues. Notable programs include the upcoming specialization in Nuclear Reactors at the National University of Medellin, scheduled for the second half of 2024, and the ongoing second cohort of the Diploma in Nuclear Energy at the University of Antioquia. Additionally, Javeriana University has been instrumental in hosting forums dedicated to nuclear applications. Moreover, the Technological University of Pereira has implemented scholarship programs for its Master's degree in Safe and Reliable Nuclear Applications (SARENA). These educational initiatives are crucial in cultivating a skilled workforce proficient in nuclear technologies.

Additionally, establishing or enhancing a nuclear regulatory body is crucial to align with international safety standards, covering safety, emergency preparedness, and waste management policies [10]. Public perception and acceptance also pose challenges, requiring transparent communication and community engagement to highlight the economic, environmental, and safety benefits of nuclear technology. Despite these hurdles, the potential for enhanced energy security, economic growth, and significant carbon emission reductions positions nuclear energy as a viable option for Colombia's sustainable and prosperous future.

## SMR as a Strategic Option

SMRs represent a significant advancement in nuclear technology and are increasingly seen as a viable option for developing countries like Colombia, aiming to diversify their energy sources while addressing the challenges associated with traditional nuclear reactors. SMRs, by virtue of their smaller size, reduced capital costs, and enhanced flexibility, offer a tailored solution to meet Colombia's specific energy needs. Their integration into the national grid could effectively complement and stabilize the variable outputs from existing renewable sources like hydro, solar, and wind.

The Mining and Energy Planning Unit (UPME), in charge of the national energy plan (PEN) 2022-2052, has foreseen in the scenarios of inflection and disruption, the progressive implementation of small modular reactors in response to the growth of demand electrification and the need to expand generation capacity [14]. A first addition of 300 MW is foreseen in 2038 and progressively until reaching 1884 MW of nuclear energy incorporated in the energy matrix.

SMRs distinguish themselves from traditional nuclear reactors in several key aspects [11]:

* Size and Scalability: SMRs are compact and modular, which means they can be manufactured at a central facility and transported to a site for assembly. This modularity not only reduces the overall footprint of the nuclear power plant but also allows for scalability. Colombia could start with a small nuclear capacity and expand incrementally as demand grows or as funding allows, minimizing the initial economic burden.
* Cost-Effectiveness: The initial investment required for SMRs is considerably lower than that for traditional reactors. This cost-effectiveness stems from the standardized production of modular components, which can benefit from economies of series production and shorter construction times. This aspect is particularly appealing for Colombia, where large-scale investments in infrastructure must be carefully balanced with other economic priorities.
* Flexibility and Integration: SMRs can be integrated more easily into existing power grids with less disruption and can be used to supplement intermittent renewable energy sources. They can be deployed in remote or off-grid locations, effectively supplying power to areas without robust infrastructure, which is a considerable advantage for a geographically diverse country like Colombia.

The operational benefits of SMRs include enhanced safety features. Modern SMR designs incorporate passive safety systems that do not require active operations for a safe shutdown, thereby reducing the risk of operator error and lessening the impact of external power supply disruptions. These safety features are engineered to contain and manage any potential malfunctions within the reactor itself, significantly diminishing the risk of widespread contamination [12].

Economically, SMRs offer a sustainable investment for Colombia's energy sector by reducing dependence on fossil fuels and addressing the variability of renewable energy, thus stabilizing energy costs and supply, key for economic stability and growth. By examining Bolivia’s successful integration of SMRs into its energy plan, Colombia can see the benefits of proactive nuclear policies and investments, providing a robust model for a sustainable and comprehensive national energy strategy.

## STRATEGIC RECOMMENDATIONS FOR COLOMBIA

To harness the full potential of SMRs, Colombia needs to undertake strategic actions aimed at building a robust nuclear framework. These recommendations are designed to address key areas necessary for the successful integration of nuclear technology into Colombia’s energy portfolio, enhancing both national energy security and environmental sustainability.

* Colombia’s entry into the nuclear energy sector requires a significant upgrade in infrastructure and capabilities. Key to this upgrade is the establishment of a comprehensive support system for nuclear technology that includes both physical infrastructure and intellectual capital.
* Continue development of Academic and Training Programs: Building a skilled workforce is crucial for the sustainable development of nuclear energy. Colombia should invest in more educational programs at universities and technical schools that focus on nuclear sciences and engineering. This initiative could be supported by partnerships with international institutions that have expertise in nuclear technology and training.
* Enhancement of Regulatory Frameworks: Robust regulatory frameworks are essential for the safe operation of nuclear facilities. Colombia should aim to develop or enhance its nuclear regulatory body by adopting best practices and standards set by international nuclear safety organizations, such as the International Atomic Energy Agency (IAEA). This involves the formulation of stringent safety protocols, emergency preparedness plans, and waste management strategies, ensuring that all aspects of nuclear energy deployment are governed by a comprehensive and transparent regulatory regime.

International cooperation is vital for accessing advanced nuclear technologies and learning from the experiences of established nuclear-powered nations.

* Technology and Knowledge Transfer: Engaging in bilateral or multilateral agreements with countries that have advanced nuclear technology can facilitate the transfer of knowledge and technical expertise to Colombia. Such partnerships might include joint research initiatives, technology sharing agreements, and personnel exchange programs, which can accelerate the development of Colombia's nuclear capabilities and ensure adherence to global standards of safety and efficiency.
* Continued support and backing from the IAEA are pivotal for ongoing enhancements in Colombia's national regulatory framework for nuclear applications. In December 2023, experts from the IAEA facilitated a Nuclear Law Workshop aimed at addressing several critical aspects. This workshop covered topics related to the components of national legislation, the international legal framework governing nuclear safety and security, as well as protocols for safeguards and the global civil liability regime for nuclear damage [15].

Public acceptance is critical for the success of nuclear projects. Misconceptions about nuclear energy can lead to significant opposition, which can derail even the most well-planned nuclear programs.

* Transparent Communication Strategies: Establishing clear and open communication channels to inform and educate the public about the benefits and risks associated with nuclear energy is essential. This should include regular updates on nuclear projects, public consultations, and educational campaigns that address common concerns and highlight the safety, environmental, and economic benefits of nuclear energy.
* Community Involvement Programs: Involving communities in the planning and decision-making processes related to nuclear facilities can enhance trust and acceptance. Community engagement initiatives could include public forums, workshops, and visits to nuclear facilities, providing firsthand information about nuclear operations and safety measures.

By implementing these strategic recommendations, Colombia can effectively prepare for the integration of nuclear energy into its national energy strategy. This approach will not only help Colombia meet its future energy demands but also contribute to its economic growth and environmental goals, positioning the country as a leader in clean and innovative energy solutions in the region.

## Conclusion

The deployment of SMRs in Colombia presents a strategic opportunity to transform its energy landscape by enhancing energy diversity and security, aligning with global sustainable development trends and addressing climate change through reduced carbon emissions. Despite historical challenges in Latin America related to socio-economic constraints, limited technological infrastructure, and public apprehensions due to global nuclear incidents, the modern nuclear industry, especially SMRs provide scalable energy solutions tailored to Colombia’s unique geographic and economic needs, potentially overcoming past barriers.

The strategic implementation of SMRs in Colombia is poised to overcome the intermittent nature of traditional renewable sources such as solar and wind. Unlike these sources, nuclear power provides a constant output, ensuring a stable energy supply that can support the nation’s development ambitions without the unpredictability of hydroelectric power, which can be compromised by seasonal and climatic variations. This aspect of nuclear energy is crucial for Colombia, considering its past energy crises triggered by droughts affecting its hydroelectric capacity.

The integration of SMRs into Colombia's energy matrix could significantly enhance its ability to meet national greenhouse gas reduction goals. This investment could also make Colombia a leader in the clean energy transition within the region. Additionally, developing a nuclear sector with SMRs would stimulate technological and industrial growth, creating high-skilled jobs, promoting scientific research, and developing a high-tech supply chain. This could transform Colombia from a consumer to an innovator and exporter of nuclear technology, particularly in Latin America where such capabilities are limited. To realize these benefits, Colombia needs a comprehensive strategy that includes developing a robust legal and regulatory framework, improving public perception of nuclear energy through transparent dialogue, and ensuring environmentally and socially responsible infrastructure development. Thus, deploying SMRs strategically could pivotally enhance Colombia's energy security and sustainability, marking a new era in its energy history.

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References

[1] GARSIDE, M. Nuclear electricity generation in Latin America in 2022, by country (2024), https://statista.com/statistics/1154008/latin-america-nuclear-electricity-generation-country/

[2] DYCK, E. IAEA Department of Nuclear Energy. IAEA Meeting Discusses Nuclear Power Options in Latin America (2015), https://www.iaea.org/newscenter/news/iaea-meeting-discusses-nuclear-power-options-in-latin-america

[3] WORLD NUCLEAR ASSOCIATION. NUCLEAR POWER IN ARGENTINA (2024), https://world-nuclear.org/information-library/country-profiles/countries-a-f/argentina

[4] WORLD NUCLEAR ASSOCIATION. NUCLEAR POWER IN BRAZIL (2024), https://world-nuclear.org/information-library/country-profiles/countries-a-f/brazil

[5] ARGUELLO, I. (2010). NUCLEAR ENERGY IN LATIN AMERICA: BETWEEN ECONOMIC DEVELOPMENT AND PROLIFERATION RISKS. Security Index: A Russian Journal on International Security, 16(4), 73–84. https://doi.org/10.1080/19934270.2010.525889

[6] WORLD NUCLEAR ASSOCIATION. NUCLEAR POWER IN BRAZIL (2024), https://world-nuclear.org/information-library/country-profiles/countries-g-n/mexico

[7] DIEGO OTERO PRADA (2016), War Spending in Colombia 1964 - 2016: $179 billion dollars lost, https://indepaz.org.co/wp-content/uploads/2018/09/Los-Gastos-de-la-Guerra.pdf

[8] SINERGOX, XM (2024), https://sinergox.xm.com.co/oferta/Paginas/Informes/CapacidadEfectiva.aspx

[9] MINISTERIO DE AMBIENTE Y DESARROLLO SOSTENIBLE (2023), https://www.minambiente.gov.co/cop28/

[10] GALEANO, D. Periódico de la Universidad Nacional (2024), El éxito de la era nuclear en Colombia dependerá de la articulación entre la academia, la industria y el gobierno.

[11] PIORO, I.L, et al. Handbook of Generation IV Nuclear Reactors (Second Edition), Current status of SMRs and S&MRs development in the world, https://www.elsevier.com/books-and-journals/book-companion/9780128205884

[12] POPOV, O., FININ, G., IVASCHENKO, T., IATSYSHYN, A., & HRUSHCHYNSKA, N. (2023). Current State and Prospects of Smallmodule Reactors Application in Different Countries of the World. In Systems, Decision and Control in Energy IV: Volume IІ. Nuclear and Environmental Safety (pp. 3-21). Cham: Springer Nature Switzerland.

[13] DEPARTAMENTO NACIONAL DE PLANEACIÓN

https://colaboracion.dnp.gov.co/CDT/Conpes/Econ%C3%B3micos/4075.pdf

[14] UNIDAD DE PLANEACIÓN MINERO ENERGÉTICA (UPME).

https://www1.upme.gov.co/DemandayEficiencia/Documents/PEN\_2020\_2050/Actualizacion\_PEN\_2022-2052\_VF.pdf

[15] MINISTERIO DE MINAS Y ENERGÍA.

https://www.minenergia.gov.co/es/sala-de-prensa/noticias-index/colombia-avanza-en-el-fortalecimiento-de-su-marco-jur%C3%ADdico-nuclear/