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Artificial Intelligence for Early-Stage Planning of Carbon Capture, Utilization, and Storage (CCUS) Networks in Colombia: A Geospatial and Generative Modeling Framework

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Abstract

This working paper presents an integrative methodological framework for early-stage planning of Carbon Capture, Utilization, and Storage (CCUS) networks in Colombia. The framework combines geospatial clustering, machine learning forecasting, and generative artificial intelligence (AI) to support the identification of emission hotspots, the prediction of CO_2 flows, and the conceptual simulation of logistics configurations. Historical emissions data (2000–2022), spatial infrastructure layers, and sectoral indicators are used to define high-priority clusters through geospatial intelligence methods such as kernel density estimation and DBSCAN. Long Short-Term Memory (LSTM) and XGBoost models are employed to forecast CO_2 capture volumes under different macroeconomic and regulatory scenarios, while SHAP values improve model interpretability. Generative AI (GPT-4o) is integrated to simulate context-aware supply chain designs, yielding conceptual configurations that can guide stakeholder engagement and territorial planning. The proposed methodology provides a decision-support architecture that bridges spatial data analytics and artificial reasoning to inform CCUS deployment in fragmented and data-scarce environments. The study contributes to the international discourse on low-carbon transitions by offering a scalable and adaptable planning toolkit, grounded in Colombia's institutional and territorial realities.

Keywords: carbon capture utilization and storage (CCUS); Colombia; artificial intelligence; geospatial clustering; LSTM; XGBoost; generative planning; emission forecasting; low-carbon infrastructure; energy transition

1. Introduction

Carbon Capture, Utilization, and Storage (CCUS) technologies are gaining global momentum as critical enablers in the transition toward net-zero emissions, particularly in hard-to-abate sectors such as cement, steel, and petrochemicals [1]. The deployment of CCUS allows for the direct capture of CO_2 at source points, its transportation through dedicated infrastructure, and subsequent injection into geological formations or integration into industrial reuse pathways [2]. Countries such as China, the United States, and the United Kingdom have already implemented national strategies to scale CCUS, highlighting its strategic role in deep decarbonization portfolios [3]. Global investment trends show a rising number of pilot and commercial-scale projects, reflecting not only technological maturity but also growing regulatory and financial support [4]. However, challenges remain regarding storage site characterization, permitting, and inter-sectoral coordination [5]. These complexities underscore the need for holistic system-level planning and innovative modeling tools to guide early-phase infrastructure decisions [6], [7].

From a techno-economic perspective, the optimization of CCUS networks requires integrating capture node selection, multimodal transport configurations, and storage location viability under multiple policy scenarios [8]. Several studies have proposed multi-objective optimization frameworks to design resilient and cost-effective CO_2 value chains, including approaches that incorporate dynamic supply-demand matching and policy-sensitive investment timing [8], [9], [10]. Moreover, environmental assessments such as life-cycle analysis (LCA) are increasingly embedded into the evaluation of CCUS pathways to align with circular economic principles and sustainable energy transitions [11]. Despite the complexity, computational advances have facilitated the simulation of large-scale networks, especially when combined with scenario analysis and uncertainty quantification [12], [13]. The adoption of digital twins and AI-supported analytics is further enhancing the real-time configurability of these systems [14]. These developments are especially relevant as countries face rising pressures to define credible pathways toward climate neutrality.

Artificial intelligence (AI) has emerged as a powerful complement to mathematical optimization in CCUS planning [15]. Machine learning (ML) techniques such as LSTM and XGBoost have demonstrated capacity to forecast emissions profiles, classify industrial sources, and support predictive asset placement under variable operational conditions [14]. Generative models like GPT-4o have recently been explored for conceptual logistics planning, scenario simulation, and constraint-driven design of territorial layouts [16], [17]. Additionally, agent-based modeling (ABM) and reinforcement learning are being employed to capture decentralized decision-making across CCUS actors, enhancing system flexibility and resilience. These tools are particularly useful during early-stage planning, when uncertainty is highest and flexibility is most needed [1]. Nevertheless, most of these applications remain concentrated in high-income countries, leaving a gap in their adoption for Latin American CCUS strategies.

Geospatial analysis is also central to CCUS design, allowing for the identification of emission clusters, transport corridors, and geological reservoirs [18]. Geographic Information Systems (GIS) and clustering algorithms have been applied to detect optimal sitting patterns and evaluate terrain constraints [7], [19]. Several recent studies advocate for integrated spatial modeling frameworks that combine industrial emissions data, infrastructural mapping, and socioeconomic indicators to inform national CCUS master plans [14], [20]. Particularly in topographically diverse countries, spatial considerations can significantly impact infrastructure costs, social acceptability, and deployment timelines. Advanced geospatial tools are now being used to generate synthetic networks and simulate deployment scenarios, often with the help of AI-assisted design algorithms [21]. These approaches are crucial for early decisions before making investment commitments.

In the Colombian context, the need for CCUS integration has been highlighted in various decarbonization and energy transition studies. The country's commitment to a 51% reduction in emissions by 2030 under its updated NDCs [22] compels the inclusion of mitigation strategies beyond renewable energy expansion. Colombia hosts significant emission-intensive clusters, particularly in the cement, coal, petrochemical, and oil refining sectors [23]. These clusters provide opportunities for localized capture but require integrated logistical strategies to enable cost-effective transport to offshore or inland storage basins [24], [25], [26]. Geological potential for CO_2 storage has been identified in basins such as Cesar-Ranchería, Middle Magdalena, and Sinú-San Jacinto, though detailed reservoir characterization remains in preliminary stages [27]. As such, CCUS planning in Colombia remains a conceptual effort, hindered by data limitations, institutional fragmentation, and a lack of enabling regulatory frameworks.

Recent academic and technical studies have begun to map potential CO_2 flows and assess transport routes using GIS-based clustering techniques [28]. For instance, Suárez Bermúdez et al. [24] evaluate capture–transport–storage pathways in the Colombian Caribbean region, identifying both geological capacity and logistical barriers. Moreover, Plazas-Niño et al. [29] highlight that incorporating CCUS into national energy strategies would require dedicated coordination across territorial entities, energy agencies, and environmental regulators. Colombia's industrial dispersion, mountainous topography, and limited infrastructure investment increase the complexity of network design. In this setting, early-stage planning models—supported by AI and spatial analytics—can offer a feasible pathway to align technological potential with territorial conditions. These models can also help identify priority clusters, simulate deployment timelines, and evaluate socioeconomic trade-offs.

Despite growing recognition, CCUS remains largely absent from Colombia's formal energy planning instruments and financing strategies. There is no national roadmap, legal definition of carbon storage liability, or integrated permitting process for cross-sector infrastructure. Nevertheless, the availability of spatial data, emissions inventories, and AI tools provides a window of opportunity for conceptual planning. In this working paper, we explore how AI-based forecasting (using LSTM/XGBoost), geospatial clustering, and generative modeling (GPT-4o) can inform early-stage design of CCUS networks in Colombia. Our goal is to contribute a replicable, flexible, and data-informed framework to guide future policy and investment decisions. This leads us to the central research question: How can artificial intelligence and geospatial tools be integrated to support the conceptual planning of CCUS infrastructure in Colombia under conditions of data scarcity and institutional uncertainty?

1.1. Contribution

This paper proposes a theoretical framework for the strategic design of CCUS supply chains in Colombia, grounded in a thorough literature review, territorial characterization of major emission clusters, and the exploratory use of AI tools to simulate logistics configurations adapted to national conditions. Unlike optimization-based approaches that rely on mixed-integer programming, this work adopts a qualitative and conceptual perspective, establishing a foundation for future research and case-based applications. The framework incorporates key components such as multicriteria analysis, territorial governance, regulatory feasibility, and the adaptive capacity of existing infrastructures, aligned with national policy instruments like the Energy Transition Roadmap and Colombia's National Development Plan [30].

Study offers an original contribution to the carbon management literature by proposing a geospatially driven and AI-assisted framework for conceptualizing carbon capture, utilization, and storage (CCUS) supply chains in emerging economies, using Colombia as a case study. While most academic contributions in this field focus on detailed techno-economic modeling and mathematical optimization (e.g., MILP, multi-objective programming), this work addresses the preliminary planning stages where data scarcity, institutional fragmentation, and regulatory uncertainty are prevalent—yet critical for decision-making.

The primary contribution lies in integrating geospatial data, emission inventories, and artificial intelligence techniques to identify industrial emission clusters, predict future CO_2 flows, and generate hypothetical logistics configurations in a computationally lightweight and accessible way. Specifically, the study proposes a dual-use of AI: (i) supervised learning methods such as XGBoost and LSTM to forecast carbon flows based on historical, spatial, and industrial features; and (ii) generative models such as GPT-4o to simulate alternative network configurations and evaluate conceptual viability based on context-sensitive criteria.

Second, the paper focuses explicitly on the Colombian industrial and territorial landscape, filling a critical gap in Latin American CCUS research. Although global studies have addressed regional deployment strategies—such as in Europe [6], China [31]—very few analyses tailor their assumptions, variables, or scenarios to the realities of Andean or tropical developing economies. In contrast, this study incorporates spatial patterns of industrialization, logistical bottlenecks, regulatory asymmetries, and geological storage potential specific to Colombia's subnational regions.

Third, the work contributes methodologically by illustrating how early-stage decision support tools can be developed without relying on full-scale numerical solvers or proprietary optimization software. This approach lowers the barriers to entry for institutions and policymakers in the Global South, particularly when initial investments and technical capacity are limited. The methodological flow—from geospatial clustering and emissions forecasting to generative logistics simulation—can serve as a replicable template for conceptual CCUS planning in other countries with similar constraints.

Finally, the paper also aligns with emerging trends in digital decarbonization, in which AI is not only a computational aid but a cognitive partner in envisioning resilient, adaptive, and context-specific low-carbon infrastructure. The use of language-based generative AI (like GPT-4o) as a planning co-pilot reflects a novel and underexplored dimension of intelligent systems applied to sustainability transitions.

In sum, we argue that the integration of georeferenced data, artificial intelligence techniques, and systemic conceptual models can support the early-stage design of CCUS systems in Colombia, lowering investment risk, improving territorial alignment, and enabling anticipatory planning under regulatory, technological, and climatic uncertainty.

2. Literature Review

The deployment of carbon capture, utilization, and storage (CCUS) networks has garnered increasing attention as a key pathway toward decarbonizing industrial economies. Over the past decade, a growing body of literature has focused on the techno-economic design of CCUS supply chains, exploring optimal configurations for CO_2 capture, transport, and storage through mathematical programming and life cycle assessment (LCA) methodologies. Foundational studies such as Wang et al. [9] and Wiltink et al. [32] have demonstrated the value of mixed-integer linear programming (MILP) for CCUS supply chain design under constraints of cost, emissions, and technology availability. Other works have expanded the modeling scope to include economic incentives, carbon trading mechanisms, and integration with renewable energy sources.

Recently, literature has increasingly integrated geospatial and territorial perspectives into CCUS network planning. For example, Vulin et al. [33] applied spatial clustering techniques to identify optimal CO_2 source-sink pairings in Europe, considering existing infrastructure and topographic barriers. Similarly, Zhou et al. [28] conducted regional assessments of emission densities and geological storage potential, using GIS tools to inform strategic location decisions. These studies highlight the critical role of geography in shaping viable CCUS logistics, particularly in countries with complex terrain or dispersed industrial hubs.

Machine learning has also emerged as a powerful tool for forecasting carbon flows and supporting CCUS planning. For instance, Shen et al. [34] employed long short-term memory (LSTM) models to estimate future emissions from Gulf-based industrial clusters under various decarbonization scenarios. XGBoost and other ensemble methods have been used to predict CO_2 capture rates and optimize decision variables in dynamic environments [14]. These techniques offer high flexibility and accuracy in handling nonlinear relationships, uncertainty, and sparse datasets—conditions often present in emerging economies like Colombia.

While predictive models offer insights into emissions trends, generative artificial intelligence remains underexplored in the context of CCUS infrastructure planning [16]. However, recent works have started to explore generative techniques to simulate alternative network designs, especially in early-stage planning where hard data may be limited [35], [36], [37]. GPT-like models have been proposed for use in scenario generation, policy simulation, and concept development, offering novel pathways for participatory and adaptive planning approaches [38]. Although their application in CCUS remains nascent, the integration of natural language generation with geospatial and technical constraints presents a promising avenue for research.

In Latin America, contributions to CCUS literature remain limited. Only a handful of studies have addressed region-specific challenges, such as low policy maturity, high infrastructural gaps, and limited institutional coordination. Delgado et al. [23] is among the few to explore CCUS potential in Colombia, highlighting geological and industrial opportunities, but lacking a systems-oriented

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design framework [24]. This gap underscores the need for tailored conceptual frameworks that address the territorial, technological, and regulatory uniqueness of countries in the Global South.

The literature on Carbon Capture, Utilization, and Storage (CCUS) has expanded considerably in recent years, reflecting its critical role in decarbonizing hard-to-abate sectors and achieving net-zero emissions. However, the integration of AI-assisted planning, geospatial emission clustering, and national-level logistics design remains fragmented. This section synthesizes relevant developments across three major domains: (i) optimization and supply chain design in CCUS systems, (ii) machine learning and forecasting of CO_2 flows, and (iii) generative AI and conceptual infrastructure planning. Particular attention is paid to how these approaches could be adapted to countries in the Global South, such as Colombia.

2.1. Optimization Models and CCUS Supply Chain Design

CUS supply chains have traditionally been modeled using mathematical optimization techniques—particularly mixed-integer linear programming (MILP) and multi-objective formulations. These models aim to determine optimal locations for capture, transportation, and storage facilities under constraints of cost, carbon intensity, capacity, and infrastructure availability [19], [39]. For instance, Zhang et al. [10] proposed a two-phase optimization model considering capture sources and sink compatibility, with a special focus on minimizing environmental and economic trade-offs. Similarly, Li et al. [40] applied a robust optimization approach to capture uncertainties in carbon allowance allocation across multi-regional clusters.

Hanson et al. [2] developed a profit-driven expansion model that optimizes the CCUS network across time, balancing carbon mitigation with economic feasibility. In parallel, Rakhiemah et al. (2025) explored a multiscale framework that integrates carbon capture, transportation, and enhanced oil recovery (EOR), highlighting its applicability in oil-rich regions [41]. These models, while highly rigorous, often require high-quality data, computational resources, and full institutional support—conditions not always present in low- and middle-income countries. Despite their technical sophistication, optimization models rarely incorporate the spatial diversity and logistical challenges inherent in countries with fragmented industrial networks or limited infrastructure, such as Colombia. In response, recent studies have begun integrating geographic information systems (GIS) to inform optimization variables, allowing for more realistic and regionally adapted designs [28].

Moreover, optimization literature has traditionally treated CO_2 as a homogeneous flow, overlooking variabilities in emission type (biogenic vs. fossil), stream concentration, and temporal intermittency [7]. More recent studies—such as [6] and [42] —began to tackle this heterogeneity through modular transport modes and flexible node activation, but such innovations remain underrepresented in Latin American scenarios.

2.2. Machine Learning for CO_2 Forecasting and Emission Dynamics

The use of machine learning (ML) in CCUS has grown to forecast CO_2 emissions, estimate capture potential, and inform decision-making under uncertainty. Supervised algorithms such as gradient boosting machines (e.g., XGBoost), random forests, and support vector machines have been employed to model relationships between industrial activity and emissions output [14], [15], [37]. These models are particularly advantageous in data-scarce environments, given their robustness to noise and capacity to handle nonlinear interactions. The advantage of ML lies in its ability to process heterogeneous and sparse datasets—conditions typical in early-stage planning for countries with limited monitoring infrastructure. For instance, Kashif and Ślepaczuk demonstrate how Long Short-Term Memory (LSTM) models outperform classical regression or ARIMA in predicting CO_2 emissions in the presence of structural breaks and policy shocks [43]. Some models integrate ML outputs into decision support systems, serving as inputs for techno-economic simulations or for probabilistic modeling of demand and supply [44], [45]. This modularity is critical for contexts where full MILP deployment is premature. However, a key limitation is the lack of interpretability in black-box models, which complicates regulatory adoption and policy dialogue.

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In particular, LSTM networks—designed to retain long-range dependencies in time series—are well-suited to forecasting emissions influenced by seasonal or cyclical factors [46]. LSTM networks, combining with Graph Convolutional Networks (GCN) [47], have proven useful in capturing temporal dependencies in emission data, offering more accurate forecasts than traditional time-series models. Applications include predicting capture loads at industrial sites, forecasting CO_2 transportation volumes, and identifying emission spikes due to policy or production shifts.

To address this, interpretable ML methods such as SHAP (SHapley Additive exPlanations) and Recurrent neural networks (RRN) are increasingly being proposed for use in CCUS-related forecasting [48], [49]. Still, most case studies remain focused on countries with robust data collection systems (e.g., China, the UK, the US), and there is little evidence of systematic application in South America. These approaches highlight a growing shift toward hybrid modeling frameworks, where ML outputs inform constraints or objectives in traditional optimization models. However, there is still limited deployment of such models in real-world national contexts, particularly in Latin America, where data availability, regulatory clarity, and inter-institutional coordination remain limited.

2.3. Generative AI and Conceptual Infrastructure Planning

While ML models are increasingly used for prediction, the literature remains scarce on the use of generative AI for infrastructure design in CCUS [14]. Yet, this area shows immense potential, especially for early-stage planning under high uncertainty. Generative pre-trained transformer (GPT) models [17], like GPT-4o, offer a novel capability: generating plausible network configurations, policy scenarios, and implementation strategies from high-level prompts and unstructured data inputs. The emergence of generative artificial intelligence (GenAI)—especially large language models (LLMs) like GPT-4o—has opened a new frontier in infrastructure planning [50], [51]. While still in early phases, these tools have shown promise in generating planning scenarios, conceptual layouts, and even pre-feasibility diagnostics in sectors like architecture, energy systems, and mobility [52].

In other sectors, generative models have been applied to simulate architectural layouts [53], route alternatives [35], and stakeholder mapping [54] in the absence of detailed design specifications (e.g., GPT-based urban planning assistants) [55]. In CCUS, this could translate into scenario generation for pipeline routes, siting logic for storage hubs, or pre-feasibility screening of regional clusters—all of which are currently labor-intensive and assumption-driven processes [56]. Despite their current underutilization, the integration of such tools could democratize planning processes and lower the entry barrier for countries like Colombia to engage in large-scale decarbonization efforts.

Moreover, studies such as [57], [58] have begun to incorporate conceptual digital twins and AI-based diagnostics to test system robustness and resilience. These tools can support iterative and adaptive design, even before complete datasets are available. Application of GenAI remains nascent. However, recent literature points to its potential in generating plausible CO_2 transportation networks, proposing hypothetical infrastructure configurations, and conducting initial design iterations without complete datasets [35]. For instance, AI-generated proposals could serve as a starting point for stakeholder consultation or participatory planning, especially in decentralized contexts like Colombia's where top-down mandates are less effective.

Moreover, GenAI could bridge the gap between technical knowledge and territorial governance. Through natural language processing and semantic analysis, these models can synthesize regulatory frameworks, translate technical constraints into planning logic, and simulate responses to policy shifts—functions critical for regions with fragmented institutional capacities. The 2025 work on safety-driven CCUS design [46] hints at this potential by exploring how digital simulations can be co-constructed by planners and algorithms.

Despite their benefits, generative models require robust prompt engineering and careful validation, especially when applied to critical infrastructure. They should be considered not as decision-makers but as planning co-pilots. Their integration with traditional models—via human-in-the-loop architectures—is a promising research avenue yet to be fully explored in CCUS systems.

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Critical Gaps and Relevance for Colombia

Despite the global advancements, significant gaps remain. There is a clear lack of integrative studies that combine ML-based forecasting, geospatial clustering, and generative simulation into a coherent planning framework. Additionally, most CCUS models assume institutional maturity and financial capacity, conditions not met in Colombia. Very few studies incorporate Latin American emissions profiles, infrastructure constraints, or policy limitations.

Study addresses these gaps by proposing a hybrid, theoretically grounded framework adapted to the Colombian context. It builds on the spatial logic of georeferenced emissions, augments insights through machine learning, and proposes the novel use of generative AI as a conceptual co-planner. This approach, while not solving the entire technical modeling challenge, provides a structured entry point for strategic CCUS design under uncertainty. This paper proposes a response: a hybrid conceptual framework combining geospatial clustering of emissions, machine learning–based forecasting of CO_2 flows, and generative AI–assisted logistics simulation, specifically adapted to the Colombian context. Rather than aiming for final optimization, this framework seeks to support early-stage exploration, reduce initial uncertainty, and enable informed stakeholder engagement.

3. Proposed Methodology

The methodological framework proposed in this study is designed to support the early-stage planning of carbon capture, utilization, and storage (CCUS) networks within the Colombian context. It integrates three core components—geospatial analysis, machine learning–based forecasting, and generative artificial intelligence–assisted simulation—into a sequential yet adaptable process. This approach acknowledges both the technical complexity of CCUS systems and the practical limitations of data, infrastructure, and governance in emerging economies. The ultimate goal is to produce a set of informed, territorially grounded, and conceptually sound scenarios that can guide future infrastructure development and policy formulation in Colombia.

The first component focuses on the geospatial identification of industrial emission clusters and potential storage zones across the national territory. This stage begins with the compilation and integration of historical CO_2 emissions data, infrastructure records, and geological suitability maps. Sources such as IDEAM and the Global Carbon Atlas provide baseline emission metrics, while national registries maintained by the UPME and the Servicio Geológico Colombiano supply critical information regarding industrial activities and subsurface storage potential. Geospatial analysis is then conducted using techniques like kernel density estimation to detect emission hotspots and spatial clustering algorithms (e.g., DBSCAN or OPTICS) to define industrial agglomerations with coherent CO_2 output profiles. This process allows for the creation of a georeferenced typology of capture-storage corridors that reflect both current emission intensities and infrastructural constraints. Additionally, a multi-criteria overlay analysis is conducted to assess the technical feasibility of nearby storage options, including saline aquifers and depleted hydrocarbon reservoirs. This territorial lens ensures that logistical and physical considerations are embedded from the outset, addressing a major shortfall in generic optimization models that disregard geography.

Following this spatial delineation, the second component involves forecasting future CO_2 flows for each cluster using supervised machine learning techniques. This forecasting is essential to size and phase the deployment of CCUS infrastructure over time, particularly under scenarios of industrial growth, energy transition, or climate regulation. Two complementary modeling strategies are applied: eXtreme Gradient Boosting (XGBoost) and Long Short-Term Memory (LSTM) neural networks. XGBoost is employed to estimate short- and medium-term CO_2 capture potential based on cross-sectional variables such as industrial output, energy consumption per sector, and macroeconomic indicators like GDP and energy intensity. LSTM models, on the other hand, are implemented to capture long-range temporal dependencies and dynamic nonlinearities inherent in emission trajectories, making them suitable for long-term forecasting under uncertainty. These models are trained using quarterly and annual data from the period 2000 to 2022, standardized and

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cleaned to ensure consistency and reliability. Model performance is evaluated using standard metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), while explainability is enhanced through techniques like SHAP (Shapley Additive Explanations), which rank variable importance and help interpret black-box predictions. The result of this phase is a robust, data-driven estimation of annual CO_2 flow volumes for each emission cluster, which will serve as quantitative input for the final design phase.

The third component of the methodology introduces generative artificial intelligence (GenAI) as a novel tool to assist in the conceptual design of CCUS logistics configurations. This stage leverages the capabilities of large language models, specifically GPT-4o, to generate infrastructure scenarios based on structured prompts derived from the outputs of the previous two stages. These prompts include detailed descriptions of cluster characteristics, forecasted CO_2 volumes, distances to viable storage sites, and existing transport infrastructure. The generative model then produces textual blueprints that simulate potential logistics networks, proposing arrangements such as centralized pipelines, modular transport loops, or phased activation routes. Each generative output is evaluated through a combination of expert review, feasibility heuristics, and alignment checks against Colombia's national energy and climate plans. Scenarios that demonstrate internal consistency, technical realism, and policy alignment are retained, while redundant or implausible proposals are discarded. This process is iterated multiple times to produce a set of alternatives, context-sensitive conceptual layouts that reflect different levels of investment, technological maturity, and regulatory engagement. Importantly, the generative stage is not intended to replace detailed engineering design or optimization modeling, but rather to serve as a low-cost, high-flexibility decision support mechanism during the exploration phase. By harnessing GenAI for scenario generation, stakeholders can visualize a range of plausible futures and initiate dialogue grounded in scientifically informed yet accessible projections. Additionally, this approach addresses a common bottleneck in developing countries where full-scale data or modeling capabilities are lacking, but where urgent planning needs exist.

The integration of these three components—territorial mapping, predictive modeling, and generative simulation—culminates in the synthesis of a planning toolkit tailored to the Colombian context. This toolkit comprises high-resolution maps of emission clusters, flow projections for each cluster over a defined planning horizon, and a portfolio of conceptually generated logistics scenarios. It also includes policy guidance regarding regulatory prioritization, investment phasing, and institutional coordination. The modularity of this methodology allows it to be updated as new data becomes available or as national strategies evolve, ensuring its relevance and adaptability over time.

By combining technical rigor with contextual awareness, the proposed methodology seeks to advance the state of CCUS planning not only in Colombia but also in other Global South countries facing similar infrastructural and governance challenges. Its contribution lies in its integrative vision, its operational realism, and its capacity to generate actionable insights through hybrid intelligence—human, algorithmic, and institutional.

4. Expected Results

The implementation of the proposed methodological framework is anticipated to yield multidimensional results across technical, spatial, institutional, and strategic domains. Although the model is currently in a theoretical phase, its integrative design—based on geospatial clustering, machine learning–based forecasting, and generative AI simulation—positions it as a high-potential tool for advancing early-stage CCUS planning in Colombia. While the framework has not yet been empirically applied, the integration of geospatial clustering, machine learning–based forecasting, and generative AI–assisted planning offers a robust platform for simulating real-world deployment scenarios in regions marked by institutional and infrastructural fragmentation. This section explores the expected outcomes of each component and discusses their broader implications, informed by comparative insights from previous international applications.

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A first major expected result is the spatial delineation of high-priority emission clusters, integrating not only CO_2 intensity but also proximity to viable storage formations and logistical infrastructure. It is expected that between five and eight clusters will emerge as priority regions, including industrial zones along the Magdalena River basin, the Valle del Cauca corridor, the Bogotá–Sabana complex, and coastal nodes such as Barranquilla and Cartagena. These findings would align with spatial typologies identified in other national studies—such as those for the United Kingdom [42], India [20], and China [25]—which revealed that clustering effects and transport cost minimization are decisive factors in the scalability of CCUS networks. The ability to localize emission basins with respect to infrastructure constraints (e.g., roads, pipelines, power grids) and geological capacity is particularly relevant in the Colombian context, where the legacy of segmented territorial planning and uneven industrial development limits the application of generic optimization models.

Forecasting outcomes are also expected to yield significant insight. By implementing LSTM models for long-term temporal prediction and XGBoost for short-term multi-factorial analysis, the model will be capable of projecting CO_2 capture flows under different economic, energy, and policy conditions. Prior applications of these models—such as the work of Gu et al. [31] in China's steel sector or Hosseinifard et al. [45] in the Middle East's petrochemical complexes—demonstrated high predictive accuracy (RMSE < 10%) and meaningful interpretability through SHAP-based analysis. It is expected that in Colombia, a similar approach will allow for the identification of key drivers of emissions, including sectoral energy mix, regulatory evolution, and macroeconomic volatility. These projections will provide crucial input for determining infrastructure sizing, transport corridor phasing, and investment prioritization. Moreover, the integration of model explainability will facilitate transparency in decision-making and institutional uptake, a gap often identified in earlier techno-economic CCUS studies [2], [59].

A particularly novel and promising output is the set of conceptual logistics scenarios generated through large language models such as GPT-4o. Drawing from spatial and flow data, these generative simulations are expected to produce plausible, context-aware infrastructure blueprints including centralized backbone networks, decentralized modular architectures, and hybrid corridor strategies. Similar approaches have been recently explored in simulation environments for energy transition planning [19] and infrastructure layout design [4], where generative AI was shown to increase ideation speed and conceptual coverage while preserving technical constraints encoded in the prompt structure. In the Colombian case, such simulations could serve as powerful tools for stakeholder engagement, facilitating consultation processes, feasibility discussions, and regulatory foresight. This is especially relevant given the frequent delays in infrastructure projects due to planning asymmetries, social acceptance gaps, and institutional fragmentation.

Beyond individual outputs, the synthesis of the methodology into a flexible, modular decision-support toolkit represents a major systemic contribution. The toolkit is expected to integrate spatial intelligence, predictive analytics, and generative design into a single interface, allowing planners, investors, and policymakers to navigate trade-offs, test assumptions, and compare scenarios. This type of integrative framework has been advocated in recent literature as a critical enabler for scaling CCUS in developing economies [22]. In Colombia, such a tool could bridge the divide between national climate commitments—such as the NDCs and the Estrategia 2050—and operational implementation capacity at the subnational level, where planning instruments often lack technical coherence or emissions granularity.

At the systemic level, the integration of these results is expected to produce a flexible decision-support toolkit tailored to Colombia's territorial and institutional realities. This toolkit would not only allow planners and decision-makers to visualize future CCUS networks under diverse assumptions but also enable scenario comparison under budgetary, environmental, or regulatory constraints. Additionally, it would serve as a knowledge base for future optimization and techno-economic modeling efforts, once project maturity increases and more granular data become available. From a policy perspective, the expected results hold the potential to significantly enhance coordination between national strategies such as the Plan Energético Nacional (PEN), the Estrategia de Largo Plazo 2050, and subnational territorial planning frameworks. By identifying emission hubs and logistical corridors, the framework may support targeted regulatory incentives, public-private partnerships, and infrastructure co-financing mechanisms. It can also inform international cooperation efforts focused on climate finance, technology transfer, and capacity building in line with Colombia's NDC commitments.

Moreover, the model's capacity for modular expansion and territorial adaptation makes it highly relevant for transboundary and subregional applications in Latin America. For instance, recent studies on CCUS strategies in the Southern Cone [60] and the Andean region [24] have highlighted the need for interoperable frameworks that can accommodate diverse institutional settings, legal norms, and development agendas. The proposed methodology—while piloted in Colombia—could thus be transferred or adapted to neighboring countries with similar challenges and emissions structures, enhancing regional collaboration under platforms such as the Alianza Latinoamericana para la Captura de Carbono.

In summary, the expected results from the implementation of this framework are not limited to technical forecasts or spatial mappings. Rather, they include a broader set of knowledge-based and decision-enabling tools that can accelerate the formulation, consultation, and implementation of CCUS projects in Colombia. The integration of artificial intelligence across forecasting and planning stages not only improves model performance and scalability but also expands the epistemological boundaries of infrastructure development under uncertainty. These contributions, although yet to be validated empirically, lay the groundwork for a new generation of planning instruments that are intelligent, inclusive, and territorially grounded.

5. Conclusions

This study proposes an integrative methodological framework for the early-stage planning of Carbon Capture, Utilization, and Storage (CCUS) networks in Colombia, leveraging geospatial intelligence, machine learning forecasting, and generative artificial intelligence. The framework is designed to address critical informational and institutional gaps that have historically limited the deployment of CCUS infrastructure in emerging economies, particularly in territorially fragmented contexts such as Colombia.

The expected results suggest that geospatial clustering techniques can effectively localize high-priority emission nodes that align geological storage potential and existing infrastructure corridors. Additionally, machine learning models—such as LSTM and XGBoost—are expected to produce accurate forecasts of CO_2 flows, while offering interpretability through SHAP analysis to support transparent policy and investment decisions. The integration of generative AI models, including GPT-4o, into the planning process introduces a novel capability: generating conceptual infrastructure configurations that are technically plausible, territorially informed, and useful in early-stage stakeholder dialogues.

By combining these components into a decision-support toolkit, the framework transcends the limitations of purely techno-economic models and opens new pathways for collaborative, adaptive, and territorially grounded CCUS planning. This is especially relevant in Colombia, where regional disparities, institutional coordination challenges, and regulatory uncertainty have delayed the translation of climate ambition into concrete project pipelines.

Furthermore, this work situates itself within a growing international discourse on the need for integrative tools that bridge the gap between carbon neutrality objectives and the technical-operational realities of emission reduction pathways. While empirical validation remains the next step, the proposed architecture provides a strong conceptual and methodological foundation that can inform national policy, attract international climate finance, and facilitate public-private coordination.

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