

MULTI-CRITERION AND MULTI-SCALE ANALYSIS FOR THE SUSTAINABLE LOCATION OF DATA CENTERS IN COLOMBIA

ANÁLISIS MULTICRITERIO Y MULTIESCALA PARA LA UBICACIÓN SOSTENIBLE DE CENTROS DE DATOS EN COLOMBIA

Sánchez-Torres, G.¹, Sánchez-Cataño Malak², Henríquez-Miranda, C.³

¹ **Ph.D. German Sánchez Torres. Profesor Titular.** Programa de Ingeniería de Sistemas. Facultad de Ingenierías. Universidad del Magdalena. gsanchez@unimagdalena.edu.co. Enlace ORCID: <https://orcid.org/0000-0002-9069-0732>

² **Ing. Malak A. Sánchez Cataño. Ingeniería de Sistemas.** Programa de Ingeniería de Sistemas. Facultad de Ingenierías. Universidad del Magdalena. macsanchez@unimagdalena.edu.co. Enlace ORCID: <https://orcid.org/0009-0007-8398-5392>

³ **Ph.D. Carlos Henríquez Miranda. Profesor Asociado.** Programa de Ingeniería de Sistemas. Facultad de Ingenierías. Universidad del Magdalena. chenriquezm@unimagdalena.edu.co. Enlace ORCID <https://orcid.org/0000-0001-8252-1413>.

Entidad

Universidad del Magdalena
Carrera 32 #22-08. Santa Marta, Magdalena, Colombia.
Tel: 57-605-4381000 Ext. 3140
E-mail: chenriquezm@unimagdalena.edu.co

Recibido: 11/11/2025 / Aceptado: 05/04/2026

Resumen

La expansión de la infraestructura digital ha incrementado la necesidad de identificar ubicaciones adecuadas para centros de datos, especialmente en países donde las condiciones energéticas, climáticas, urbanas y de riesgo presentan contrastes territoriales significativos. En Colombia, esta discusión sigue siendo limitada, a pesar del crecimiento de la demanda de servicios digitales. Este estudio propone un marco de evaluación multicriterio para comparar la aptitud relativa de

diez ciudades colombianas candidatas a la ubicación de centros de datos en tres escenarios de escala: pequeña (0.5-2 MW), mediana (2-20 MW) y grande (>20 MW). La evaluación se estructuró en cinco dimensiones: soporte energético, aptitud climática, conectividad digital, riesgo territorial y escala urbana-potencial de mercado. Con base en estas dimensiones, se construyó un índice sintético de aptitud para la ubicación de centros de datos (*Data Center Siting Suitability Index*), estimado mediante una agregación ponderada por escenario. El análisis utilizó fuentes oficiales y de acceso abierto de Colombia y se complementó con pruebas de sensibilidad, tanto locales como globales. Los resultados muestran que Bogotá y Medellín presentan un desempeño consistentemente alto en los tres escenarios evaluados, mientras que Barranquilla mejora su posición relativa en el escenario de gran escala. El análisis de los resultados indica que la aptitud territorial para la ubicación de centros de datos en Colombia depende de la escala funcional del proyecto y que el marco propuesto puede apoyar, de forma preliminar, la toma de decisiones en infraestructura digital con criterios de sostenibilidad territorial y energética.

Palabras clave: centros de datos, sostenibilidad territorial, infraestructura digital, desarrollo sostenible.

Abstract

The expansion of digital infrastructure has increased the need to identify suitable locations for data centers, especially in countries where energy, climatic, urban, and risk conditions show significant territorial contrasts. In Colombia, this discussion remains limited despite the growing demand for digital services. This study proposes a multicriteria evaluation framework to compare the relative suitability of ten Colombian cities as candidate data center locations across three scale scenarios: small (0.5–2 MW), medium (2–20 MW), and large (>20 MW). The evaluation was structured around five dimensions: energy support, climatic suitability, digital connectivity, territorial risk, and urban scale–market potential. Based on these dimensions, a synthetic Data Center Siting Suitability Index was developed and estimated through scenario-specific weighted aggregation. The analysis used official and open-access Colombian data sources and was complemented by local and global sensitivity tests. The results show that Bogotá and Medellín perform consistently well across the three evaluated scenarios, while Barranquilla improves its relative position in the large-scale scenario. The findings indicate that territorial suitability for data center siting in Colombia depends on the functional scale of the project, and that the proposed framework can preliminarily support digital infrastructure decisions based on territorial and energy sustainability criteria.

Keywords: Data centers, territorial sustainability, digital infrastructure, sustainable development.

1. INTRODUCTION

The increasing digitalization of the economy, the expansion of cloud services, the growth of data traffic, and the

consolidation of compute-intensive applications have turned data centers into an increasingly critical infrastructure for the operation of firms, platforms, and public services. This functional centrality has been

accompanied by growing attention to their energy requirements, cooling needs, and connectivity demands, as well as the territorial implications of their deployment (Koot & Wijnhoven, 2021; Shuja *et al.*, 2016). Consequently, the location of a data center should not be understood merely as a real estate or logistical decision, but rather as an infrastructure decision that conditions operational performance, costs, resilience, and sustainability (Covas *et al.*, 2013; Turek & Radgen, 2021).

The literature has shown that location significantly influences the performance of these facilities. Climatic conditions affect cooling requirements and, therefore, a substantial share of energy consumption; at the same time, the availability of power infrastructure, digital connectivity, and certain territorial conditions influence the feasibility and relative attractiveness of different locations (Arzumanyan *et al.*, 2025; Turek & Radgen, 2021). For this reason, the selection of data center locations has increasingly been addressed using multicriteria evaluation frameworks and spatial analysis approaches that integrate heterogeneous variables into comparative decision-support frameworks (Covas *et al.*, 2013; Hussain *et al.*, 2026; Kheybari *et al.*, 2020). These approaches are particularly useful when the objective is not to select a specific site, but rather to conduct a preliminary screening of candidate territories or cities.

Most of the existing literature focuses on European and North American contexts, although applications in other regions are beginning to emerge. Recent studies have developed national or regional assessments to identify favorable areas for data centers in Sweden, Texas, the United

Kingdom, and Turkey, demonstrating the usefulness of combining energy, climatic, and infrastructural criteria through multicriteria evaluation techniques (Arzumanyan *et al.*, 2025; Hussain *et al.*, 2026; Jerlés *et al.*, 2024; Oztas, 2025). However, in Colombia, this problem has received considerably less attention. To the best of our knowledge, there is no simple, reproducible comparative framework for assessing the relative suitability of Colombian cities for hosting data centers in the early stages of evaluation.

This gap is relevant for several reasons. Colombia exhibits significant inter-urban contrasts in market size, fixed connectivity, climatic conditions, and energy supply, such that an aggregated territorial perspective can provide useful insights for preliminary planning and prioritization processes. Furthermore, project scale matters: a city may be reasonably attractive for a small-scale facility but may not retain that relative advantage for a large-scale project, where energy support and territorial robustness become more critical (Arzumanyan *et al.*, 2025; Turek & Radgen, 2021).

This study proposes a multicriteria evaluation framework to compare the relative suitability of 10 Colombian cities as candidate data center locations across three scale scenarios. Rather than seeking a single optimal location or modeling a specific site, the paper adopts an inter-urban analytical perspective to address the following question: *which Colombian cities offer relatively more favorable conditions for data center location when energy, climatic, connectivity, risk, and urban scale criteria are jointly considered?* This methodological approach aligns with prior studies that have

employed synthetic territorial suitability indicators to support early-stage location decisions (Arzumanyan *et al.*, 2025; Covas *et al.*, 2013; Jerléus *et al.*, 2024).

To this end, a synthetic territorial suitability index—referred to as the *Data Center Siting Suitability Index*—is constructed. The model integrates five dimensions—energy support, climatic suitability, digital connectivity, territorial risk, and urban scale—and distinguishes among three facility-size scenarios: small-scale, medium-scale, and large-scale. In addition, the analysis is complemented by local and global sensitivity tests and a comparison with a baseline scenario that uses homogeneous weighting across criteria to assess the robustness of the resulting rankings.

The main contribution of this paper is to provide a first empirical, replicable approximation to the problem of inter-urban data center location in Colombia, based on official, open data sources. In doing so, the study proposes an analytical decision-support tool that may be useful both for academic discussions on digital infrastructure, territory, and sustainability, and for preliminary planning and comparison exercises of candidate locations. In this sense, the paper does not aim to replace detailed site-level assessments, but rather to provide an initial layer of territorial evaluation upon which subsequent microlocation analyses and more refined technical assessments can be developed.

2. RELATED WORK

The literature on data centers has expanded around two major concerns,

which, although related, have not always evolved in an integrated manner. The first focuses on the energy and environmental performance of these facilities, including electricity consumption, cooling, water use, emissions, efficiency barriers, and operational sustainability strategies (Hoosain *et al.*, 2023; Jerléus *et al.*, 2024; Murino *et al.*, 2023; Newkirk *et al.*, 2024; Shuja *et al.*, 2016). The second addresses location as a spatial, multicriteria decision problem, in which the suitability of a territory depends on the combination of climatic, energy, infrastructural, environmental, and socioeconomic factors (Arzumanyan *et al.*, 2025; Covas *et al.*, 2013; Kheybari *et al.*, 2020).

This study is positioned at the intersection of both strands, with particular emphasis on the comparative evaluation of candidate cities.

One of the earliest and most relevant contributions to the location problem is the study by Covas, Silva, and Dias (Covas *et al.*, 2013), which proposed a methodology based on geographic information systems to identify the most favorable areas for new data centers in Portugal. Their work demonstrated that location can be treated as a structured decision problem rather than an opportunistic site selection. Building on this, subsequent research has reinforced the idea that data center siting requires the integration of multiple, often conflicting, criteria. In this vein, Kheybari *et al.* (Kheybari *et al.*, 2020) developed a multicriteria decision-making methodology for sustainable location, emphasizing the need to consider economic, technical, and environmental components jointly.

More recently, the literature has moved toward more comprehensive territorial analysis frameworks. Turek and Radgen (Turek & Radgen, 2021) showed that even relatively small location changes can lead to significant differences in cooling-related energy consumption, highlighting the importance of incorporating climatic variables into siting processes. In Jerlés *et al.* (Jerlés *et al.*, 2024), in a study applied to Sweden, environmental footprint assessments were combined with a territorial suitability tool for planning new data centers and evaluating existing locations. From a more explicitly spatial perspective, Arzumanyan *et al.* (Arzumanyan *et al.*, 2025) developed a geospatial suitability analysis for Texas that integrated energy, infrastructure, risk, labor, and land use, complemented by sensitivity analyses. Similarly, Hussain *et al.* (Hussain *et al.*, 2026) proposed a GIS-MCDA framework for the United Kingdom, incorporating spatial exclusions, raster standardization, and weighted aggregation of climatic and infrastructural criteria. Although at a more limited scale and using a different method, Oztas (Oztas, 2025) also emphasized the role of climatic conditions and the robustness of results through sensitivity analysis in location decision-making.

In parallel, a significant portion of the literature has focused on the broader sustainability framework of the sector. Reviews such as Shuja *et al.* (Shuja *et al.*, 2016) show that energy efficiency has been a central axis of the technical debate on data centers, while more recent works have expanded the scope toward circularity, environmental footprint, and operational sustainability perspectives (Hoosain *et al.*, 2023; Murino *et al.*, 2023). Koot and

Wijnhoven (Koot & Wijnhoven, 2021) further provide evidence on the impact of increasing digital usage on data center electricity demand, reinforcing the need to consider not only internal efficiency but also the territorial conditions in which these facilities are located.

Thus, the literature does not approach data centers solely as technical installations, but as infrastructures whose relationship with energy, territory, and sustainability must be examined in an integrated manner.

Despite these advances, three features of the literature motivate the present study. First, most empirical applications of territorial suitability are concentrated in Europe and North America (Arzumanyan *et al.*, 2025; Hussain *et al.*, 2026; Jerlés *et al.*, 2024), whereas, to the best of our knowledge, applications in Latin America remain scarce. Second, several studies rely on fine-grained regional scales, raster-based surfaces, or highly detailed spatial models that are not always easily replicable in contexts where available data are more aggregated. Third, although the literature acknowledges that location requirements depend on the type of facility, it does not always translate this insight into clear comparative scenarios that explicitly consider project scale. This aspect is particularly relevant for a country such as Colombia, where inter-urban heterogeneity may interact differently with *small-scale*, *medium-scale*, or *large-scale projects*.

In this context, the present study contributes along three dimensions. First, it extends the discussion on data center location to a national case that has been largely unexplored in the literature. Second, it proposes an inter-urban analytical

framework based on official and open data sources, prioritizing replicability and empirical feasibility over models that depend on difficult-to-access information. Third, it incorporates differentiated scenarios by facility scale to examine how the relative suitability of candidate cities changes as the importance of the energy, climatic, connectivity, risk, and market dimensions varies. In doing so, the paper situates itself within the existing literature while adapting its tools to a different problem, scale of analysis, and data context, with an emphasis on supporting territorially informed and sustainability-consistent decision-making.

3. METHODOLOGY

3.1 General Study Design

The study adopts a quantitative, comparative, and territorial screening design to evaluate the relative suitability of Colombian cities for data center locations from territorial and energy sustainability perspectives (see Figure 1). The objective is not to select a specific site nor to solve a high-resolution spatial optimization problem, but rather to construct an inter-urban screening tool that enables comparison across urban alternatives based on a compact set of observable criteria. This approach is consistent with prior studies that employ multicriteria frameworks and territorial suitability analyses to support early-stage location decisions (Arzumanyan *et al.*, 2025; Covas *et al.*, 2013; Jerléus *et al.*, 2024).

The unit of analysis consists of ten candidate cities in Colombia: Bogotá, Medellín, Cali, Barranquilla, Cartagena,

Bucaramanga, Pereira, Manizales, Ibagué, and Santa Marta.

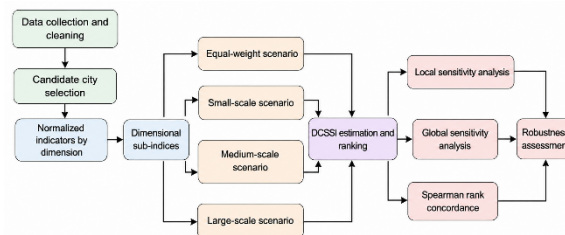


Figure 1. General outline of the methodological procedure.

Fuente. Autores.2026

Selection was based on two conditions: urban relevance within the Colombian system and operational availability of comparable data across all units. Accordingly, the study prioritizes inter-urban consistency and methodological replicability over spatial detail that would not be sustainable given the available dataset. Since the analyzed universe is limited and defined for comparative purposes, the results should be interpreted as a relative ranking exercise among candidate cities rather than as statistical inferences about a broader population of Colombian municipalities.

3.2 Facility Scale Scenarios

To incorporate the notion that location requirements vary with the functional scale of the project, the analysis is structured into three scenarios: small-scale (0.5–2 MW), medium-scale (2–20 MW), and large-scale (>20 MW). These ranges are adopted as an analytical simplification, grounded in recent technical literature, and allow for capturing plausible differences in the relative importance of the considered dimensions. In particular, the small-scale range is based on technical references that place such

facilities between 0.5 and 2 MW, while the thresholds for medium- and large-scale are defined consistently with recent taxonomies distinguishing enterprise-scale and larger installations above 20 MW (Electric Power Research Institute (EPRI), 2024; National Renewable Energy Laboratory (NREL), 2024).

Conceptually, the small-scale scenario represents facilities with greater dependence on proximity to demand and connectivity; the medium-scale scenario reflects a more balanced condition; and the large-scale scenario emphasizes the relevance of energy support and territorial robustness.

3.3 Dimensions, Variables, and Data Sources

The model is constructed around five dimensions: energy support, climatic suitability, digital connectivity, territorial risk, and urban scale–market potential. Given the comparative nature of the study, variables were selected based on observability, measurability, and availability across all cities. Table 1 summarizes the variables included in the operational version of the model, their substantive meaning, and their specific definition in this study.

Population variables were obtained from official municipal population projections provided by the National Administrative Department of Statistics (Departamento Administrativo Nacional de Estadística (DANE), 2025b), while territorial identification and municipal head coordinates were based on DIVIPOLA (Departamento Administrativo Nacional de Estadística (DANE), 2025a). Digital

connectivity was represented by the rate of fixed internet subscriptions per 1,000 inhabitants in municipal head areas, constructed from the fixed internet registry of the Ministry of Information and Communication Technologies (Ministerio de Tecnologías de la Información y las Comunicaciones (MinTIC), 2023). Climatic suitability was proxied by long-term annual mean temperature derived from climatological normals of the Institute of Hydrology, Meteorology and Environmental Studies (Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), 2024). In this case, the selection of the representative station prioritized proximity to the urban center to avoid biases from averaging stations with heterogeneous climatic conditions.

The territorial risk dimension was represented by the municipal seismic acceleration parameter AA, obtained from the Colombian Geological Survey (Servicio Geológico Colombiano (SGC), 2024). This parameter was selected for three reasons: it provides an official continuous scale, allows direct normalization, and avoids redundancy that would arise from including both general hazard categories and highly correlated parameters simultaneously. For the energy dimension, two complementary proxies were used. The first is an indicator of the scale of the electrical environment, approximated using total territorial demand reported by XM for March 2025 (XM S.A. E.S.P., 2025). The second is an ordinal indicator of functional proximity to the National Transmission System, constructed from territorial information synthesized by UPME regarding connections between the Regional Transmission System and the National Transmission System (Unidad de Planeación Minero Energética (UPME),

2025). This second variable should not be interpreted as a direct measure of available capacity, but rather as a parsimonious proxy for the structural support of the grid in the considered urban environment.

Table 1 Variables included in the operational version of the model

Dimension	Operational variable	Description and interpretation
Energy support	xm_total_demand_gwh_2025_03 XM (XM S.A. E.S.P., 2025)	Proxy for the scale of the electrical environment, defined as the total territorial electricity demand reported by XM for March 2025, associated with the departmental scope of each candidate city. (↑ higher is better)
Energy support	stn_connection_proximity_proxy UPME (Unidad de Planeación Minero Energética (UPME), 2025)	Ordinal proxy for structural grid support, defined based on the functional proximity of the city to connections between the Regional Transmission System and the National Transmission System, according to territorial information synthesized by UPME. (↑ higher is better)
Climate suitability	temperatura_mean_c (Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), 2024)	Long-term mean annual temperature at the climatological station selected as representative of the urban center. (↓ lower is better)
Digital connectivity	fixed_internet_accesses_per_1000_cabecera_2025 (Ministerio de Tecnologías de la Información y las Comunicaciones (MinTIC), 2023); (Departamento Administrativo Nacional de Estadística (DANE), 2025b)	Rate of fixed internet accesses per 1,000 inhabitants in the municipal urban center, constructed from the fixed internet registry and official population projections. (↑ higher is better)
Territorial risk	AA_SGC (Servicio Geológico Colombiano (SGC), 2024)	Municipal seismic acceleration parameter AA, used as the official continuous measure of relative seismic exposure. (↓ lower is better)
Urban scale–market potential	population_cabecera_2025 (Departamento Administrativo Nacional de Estadística (DANE), 2025b)	Projected population of the municipal urban center for 2025, used as a proxy for urban market size and potential demand mass. (↑ higher is better)

Fuente. Autores.2026

A flood risk variable was not included in the main index. This exclusion was deliberate and not merely due to data availability. Given the inter-urban scale of the study, flood risk is considered more methodologically appropriate as a micro location criterion rather than a central factor for inter-city comparison. Accordingly, the territorial risk model is restricted to the seismic component, which exhibits greater consistency at the municipal scale.

To ensure transparency in the empirical basis of the model, Table 2 presents the original values used to construct the index before normalization. This allows direct reconstruction of the transformation from observed variables to the normalized values reported later. Since functional proximity to the National Transmission System is determined by a coding decision rather than direct measurement, Table 3

documents its territorial traceability and the rule used to assign values.

3.4 Construction of the Territorial Suitability Index

The comparative evaluation is synthesized using the Data Center Siting Suitability Index (DCSSI), which is expressed on a 0–100 scale. Let $DCSSI_j$ denote the score for city j . The index is defined as:

$$DCSSI_j = 100 \sum_{k=1}^5 W_k D_{kj} \quad (1)$$

Where W_k represents the weight of dimension k and D_{kj} is the normalized sub-index of that dimension for city j . The five sub-indices correspond to energy support, climatic suitability, digital connectivity, territorial risk, and urban scale–market potential.

Each sub-index is computed from the normalized variables composing its respective dimension. In the operational version of the model, four dimensions are represented by a single primary variable, while the energy support sub-index is computed as the simple average of two components: the scale of the electrical environment and functional proximity to the National Transmission System. Equal internal weighting within this dimension is adopted as a parsimonious decision, consistent with the exploratory-comparative nature of the study and the absence of sufficient evidence to justify differential weighting. Formally:

$$D_{energy,j} = \frac{z_{1j} + z_{2j}}{2} \quad (2)$$

Table 2 Original values used in the construction of the DCSS

City	Electrical environment, XM (GWh)	Functional proximity to the STN (assigned value)	Mean annual temperature (°C)	Fixed accesses per 1,000 inhabitants in the urban center	Seismic parameter AA	Urban center population 2025
Bogotá	228.54	0.75	13.6	284.61	0.15	7,912,359
Medellín	293.61	0.75	23.1	307.21	0.15	2,479,683
Cali	276.03	0.75	24.5	242.58	0.25	2,224,562
Barranquilla	148.49	1.00	29.4	237.41	0.10	1,278,651
Cartagena	138.92	0.75	27.7	220.24	0.10	903,881
Bucaramanga	115.75	1.00	23.0	274.68	0.25	607,060
Pereira	29.07	0.75	21.9	334.08	0.25	408,608
Manizales	51.64	1.00	17.3	231.00	0.25	445,953
Ibagué	45.83	1.00	25.4	310.98	0.20	514,685
Santa Marta	31.83	1.00	28.6	207.02	0.15	521,897

Fuente. Autores.2026

Where z_{1j} is the normalized value of territorial electricity demand and z_{2j} is the normalized value of the functional proximity proxy.

To ensure comparability across variables with different scales, min–max normalization is applied. For benefit variables:

$$z_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (3)$$

For cost variables, the transformation is inverted:

$$z_{ij} = \frac{\max(x_i) - x_{ij}}{\max(x_i) - \min(x_i)} \quad (4)$$

Under this convention, higher values of z_{ij} always represent greater relative suitability. Territorial electricity demand, functional proximity to the transmission system, fixed internet penetration, and population are treated as benefit variables, while mean temperature and the seismic parameter AA are treated as cost variables.

3.5 Scenario-Based Weighting

The set of dimensions remains constant across scenarios, but their relative importance varies according to facility

scale. The weights used are reported in Table 4.

Table 3 Traceability of the functional proximity proxy to the National Transmission System (STN)

City	STN reference municipality	Reference STN substation	Reference STR substation	STN in the same municipality	Final assigned value
Bogotá	Tenjo	Bacatá	Salitre	0	0.75
Medellín	Bello	Bello	Guayabal	0	0.75
Cali	Yumbo	Yumbo	Alferez	0	0.75
Barranquilla	Barranquilla	Nueva Barranquilla	Silencio	1	1.00
Cartagena	Santa Rosa	Bolívar	Chambacu	0	0.75
Bucaramanga	Bucaramanga	Bucaramanga	Real de Minas	1	1.00
Pereira	La Virginia	La Virginia	Cuba	0	0.75
Manizales	Manizales	La Enea	Manizales	1	1.00
Ibagué	Ibagué	Mirolindo	Papayo	1	1.00
Santa Marta	Santa Marta	Santa Marta	Manzanares-Libertador	1	1.00

Fuente. Autores.2026

Weight assignment follows a substantive rationale rather than aiming to estimate empirically derived coefficients. In the small-scale scenario, greater importance is assigned to digital connectivity and urban scale–market potential, under the assumption that smaller facilities are more dependent on proximity to demand, connectivity quality, and integration within established urban nodes. The medium-scale scenario adopts a more balanced structure across energy support, connectivity, and market dimensions. In contrast, the large-scale scenario increases the weight of energy support and territorial risk, reflecting the greater sensitivity of large facilities to grid robustness and operational vulnerabilities. The equal-weight scenario is introduced as a neutral benchmark to assess the extent to which results depend on the adopted substantive weighting scheme. The potential influence of this weighting structure on the results is therefore examined explicitly through local and global sensitivity analyses.

Accordingly, the final index is computed for each scenario as a weighted combination of

sub-indices with different weighting structures. In the benchmark scenario, each dimension is assigned a weight of 0.20. This configuration allows comparison between conceptual scenarios and a neutral baseline, facilitating the assessment of ranking stability.

Table 4 Dimensional weights by scenario

Dimension	Homogeneous	Small	Medium	Large
Energy support	0.20	0.20	0.25	0.35
Climate suitability	0.20	0.15	0.15	0.15
Digital connectivity	0.20	0.30	0.25	0.15
Territorial risk	0.20	0.15	0.15	0.20
Urban scale-market potential	0.20	0.20	0.20	0.15

Fuente. Autores.2026

3.6 Sensitivity Analysis and Robustness Considerations

To evaluate model robustness with respect to reasonable variations in weights, a two-level sensitivity analysis is conducted.

First, a local sensitivity analysis is performed using deterministic perturbations of the dimensional weights. For each scenario, one dimension at a time is increased or decreased by 0.05, while the remaining weights are proportionally rescaled to maintain the unit-sum constraint. Let w_{sk} denote the base weight of dimension k in scenario s , and δ is the applied perturbation. The perturbed weight for dimension k is defined as:

$$w'_{sk} = w_{sk} + \delta \quad (5)$$

If the perturbation is applied to dimension k , the remaining weights are proportionally rescaled as:

$$w'_{sr} = w_{sr} \cdot \frac{1 - w'_{sk}}{1 - w_{sk}}, \quad r \neq k \quad (6)$$

ensuring that:

$$\sum_{r=1}^5 w'_{sr} = 1 \quad (7)$$

Second, a global sensitivity analysis is conducted through stochastic simulation of weights. For each scenario, 5,000 weight vectors are generated around the baseline structure using a Dirichlet distribution centered on the approved weights $W_s \sim \text{Dirichlet}(\alpha_s)$.

The parameter vector α_s is defined as a scaled version of the baseline weights using a concentration parameter of 60, such that $\alpha_s = 60 \cdot W_s$. For each realization, the full index and the ranking of all cities are recomputed. This approach enables estimation of leadership stability, average rank variability, and persistence of top-ranked cities. Additionally, Spearman's rank correlation is computed between rankings obtained under the equal, small, medium, and large scenarios to assess the extent to which different weighting schemes produce consistent or divergent orderings. Since the unit of comparison is the ranking rather than raw scores, this test provides a measure of ordinal stability across conceptually distinct scenarios.

These analyses enable examination of the model's internal behavior and reduce the risk that final rankings depend solely on arbitrary weight selection.

4. RESULTS

4.1 Spatial Context of Cities and Selected Variables

Figure 2 shows the territorial distribution of the ten candidate cities considered in the study. The sample covers urban nodes in both the Andean and Caribbean regions, exhibiting notable contrasts in topography, temperature, coastal proximity, urban

connectivity, and seismic exposure. This diversity provides an appropriate framework for examining inter-urban differences in territorial suitability and conditions for a potentially more sustainable location.

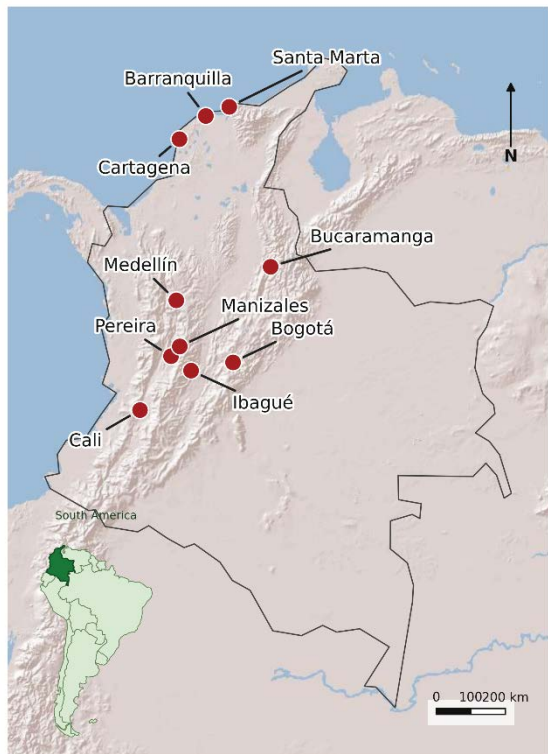


Figure 2. Candidate cities considered in the study.

Fuente Autores.2026

Figure 3 presents the behavior of the key variables included in the model. The maps of annual mean temperature and the seismic parameter AA reveal a consistent regional contrast: Caribbean cities exhibit higher temperatures and lower relative seismic hazard, while several Andean cities combine more favorable cooling conditions with comparatively higher seismic exposure. Additionally, relevant differences can be observed in fixed internet access rates and in the energy support sub-index, suggesting that territorial suitability does not depend on a single attribute but rather

on a combination of partially compensatory dimensions.

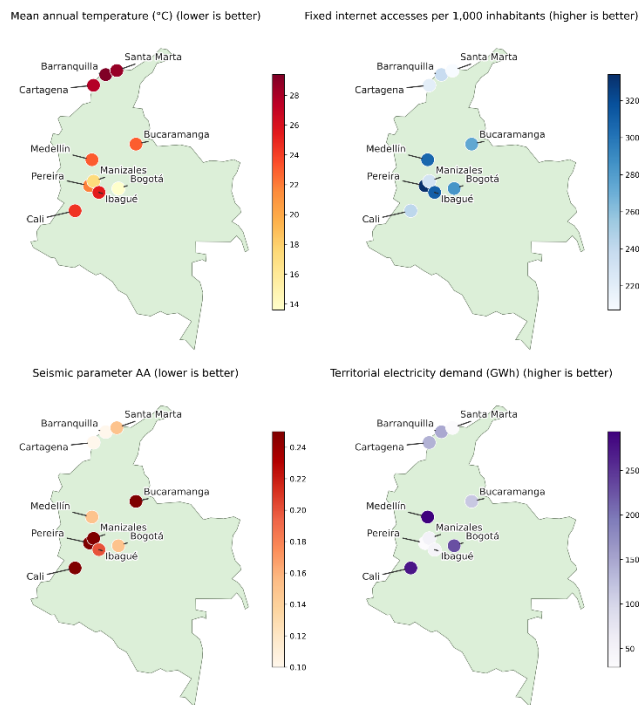


Figure 3. Spatial and comparative context of key screening variables.

Fuente. Autores.2026

Table 5 reports the matrix of normalized values used to construct the *Data Center Siting Suitability Index*. All values are expressed on a 0–1 scale and, once the appropriate benefit or cost direction is applied, higher values indicate greater relative suitability. This table allows direct observation of the relative position of each city across the variables that effectively feed the model, before the application of scenario-specific weights. As such, it constitutes the analytical bridge between territorial characterization and the subsequent computation of aggregated scores.

Table 5 Normalized values of the variables used in the construction of the DCSSI (0-1 scale)

City	Electrical environment	STN proximity	Climate suitability	Digital connectivity	Seismic risk	Urban scale
Bogotá	0.754	0.000	1.000	0.611	0.667	1.000
Medellín	1.000	0.000	0.399	0.789	0.667	0.276
Cali	0.934	0.000	0.310	0.280	0.000	0.242
Barranquilla	0.451	1.000	0.000	0.239	1.000	0.116
Cartagena	0.415	0.000	0.108	0.104	1.000	0.066
Bucaramanga	0.328	1.000	0.405	0.532	0.000	0.026
Pereira	0.000	0.000	0.475	1.000	0.000	0.000
Manizales	0.085	1.000	0.766	0.189	0.000	0.005
Ibagué	0.063	1.000	0.253	0.818	0.333	0.014
Santa Marta	0.010	1.000	0.051	0.000	0.667	0.015

Fuente. Autores.2026

4.2 City Rankings by Scenario

Figure 4 and Table 6 summarize the *Data Center Siting Suitability Index* scores across the three scale scenarios. In all cases, Bogotá ranks first and Medellín second, indicating a relatively stable advantage for these two cities when energy support, connectivity, urban scale, climate, and risk are considered jointly. However, subsequent rankings vary meaningfully across scenarios.

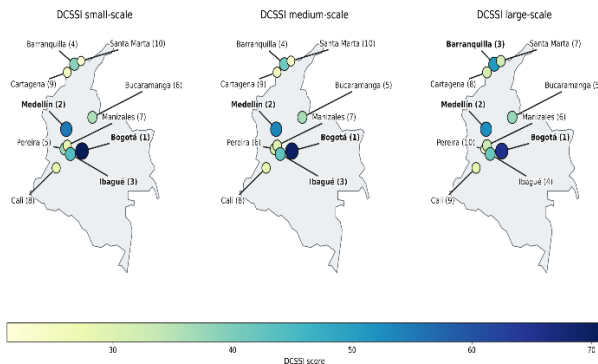


Figure 4. Territorial suitability based on DCSSI (↑) by facility-scale scenario.

Fuente. Autores.2026

In the *small-scale* scenario, Ibagué ranks third, followed by Barranquilla, Pereira, and Bucaramanga. This result is consistent with a weighting structure that prioritizes digital connectivity and urban scale, without assigning dominant importance to energy support. In the *medium-scale* scenario, the

upper ranking remains broadly similar: Bogotá, Medellín, and Ibagué occupy the top three positions, while Barranquilla remains in fourth place. In contrast, in the *large-scale* scenario, Barranquilla rises to third place, displacing Ibagué to fourth. This shift is consistent with the increased weight assigned to energy support and territorial risk in larger installations.

From a comparative perspective, the *large-scale* scenario introduces the most visible reordering. In addition to Barranquilla's rise, Santa Marta and Cartagena show relative improvements compared to the small- and medium-scale scenarios. Conversely, Pereira loses positions in the large-scale scenario and falls to last place. These changes suggest that some cities maintain stronger relative positions under configurations that favor connectivity and market-related factors, while others improve when energy support and lower seismic risk become more important.

Table 6 DCSSI scores and ranking by scenario.

City	Equal weight		Small		Medium		Large	
	DCSSI ↑	Rank	DCSSI ↑	Rank	DCSSI ↑	Rank	DCSSI ↑	Rank
Bogotá	73.09	1	70.86	1-	69.69	1-	65.69	1-
Medellín	52.60	2	55.16	2-	53.71	2-	52.78	2-
Barranquilla	41.62	3	39.01	4↓	41.44	4↓	50.73	3-
Ibagué	39.01	4	44.26	3↑	42.83	3↑	41.56	4-
Bucaramanga	32.56	5	35.86	6↓	36.51	5-	37.69	5-
Manizales	30.04	6	28.10	7↓	29.87	7↓	33.39	6-
Cartagena	29.71	7	25.21	9↓	25.73	9↓	31.43	8↓
Pereira	29.49	8	37.12	5↑	32.12	6↑	22.12	10↓
Cali	25.98	9	27.22	8↑	28.16	8↑	28.82	9-
Santa Marta	24.75	10	21.17	10-	23.69	10-	32.00	7↑

Fuente. Autores.2026

4.3 Robustness of the Ranking

Figure 5 synthesizes two complementary results from the robustness analysis: the persistence of top-ranked cities within the top three under global sensitivity, and the average ranking displacement under local perturbations by dimension.

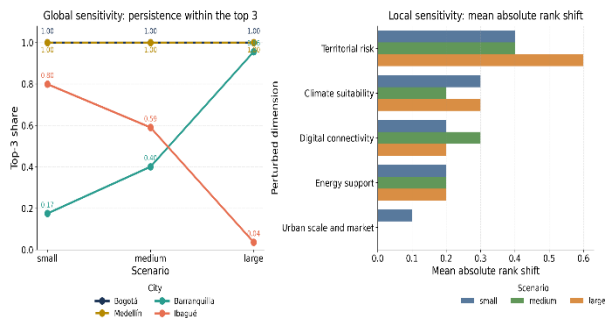


Figure 5. Robustness of scenario-based rankings based on global and local sensitivity.

Fuente. Autores.2026

The sensitivity analysis indicates that the model is reasonably stable under changes in dimensional weights. In the local sensitivity analysis, the leading city does not change across scenarios; the maximum observed ranking displacement is 2 positions in the small- and medium-scale scenarios and 3 positions in the large-scale scenario. The large-scale scenario is the most sensitive, particularly to perturbations in the territorial risk dimension; in the small-scale scenario, the most sensitive dimension is climatic suitability; and in the medium-scale scenario, the most sensitive dimension is digital connectivity.

Global sensitivity results reinforce this interpretation. Bogotá maintains near-total dominance as the top-ranked city across scenarios, with leadership shares of 99.96% in small-scale, 99.98% in medium-scale, and 98.12% in large-scale. Medellín retains a highly stable position among the top-ranked cities. At the same time, Barranquilla shows a clear gain in robustness in the large-scale scenario, remaining within the top three in 95.52% of simulations and reaching first place in a small but non-negligible share of runs. In contrast, Ibagué is stable as the third-ranked city in *small-scale* and *medium-*

scale scenarios but loses robustness in the *large-scale* case.

Rank concordance further confirms these patterns. The small- and medium-scale scenarios produce highly similar rankings, with a Spearman correlation of 0.9879. The large-scale scenario is the most differentiated, with correlations of 0.7576 and 0.8182 with the small-scale and medium-scale scenarios, respectively. Nevertheless, concordance remains positive and relatively high, indicating that differences across scenarios are not arbitrary but arise from structured changes in the relative importance of dimensions. Overall, these results indicate that the model produces an interpretable ranking with a level of robustness appropriate for inter-urban comparative analysis.

5. DISCUSSION

The results indicate that territorial suitability for data center location in Colombia cannot be understood as a uniform condition across cities, nor as a property determined by a single variable. Rather, the ranking behavior suggests that each city's relative position depends on the balance among dimensions that operate in a partially compensatory manner. This interpretation is consistent with recent literature emphasizing that data center siting should be approached as a multicriteria problem in which climate, energy, infrastructure, risk, and the urban environment interact jointly, particularly when aiming for decisions aligned with territorial sustainability and operational efficiency (Arzumanyan et al., 2025; Covas et al., 2013; Jerléus et al., 2024).

Within this framework, the consistent leadership of Bogotá and Medellín across

all scenarios can be interpreted as reflecting their comparative strength in dimensions that the model treats as structurally relevant for inter-urban screening: urban scale, digital connectivity, and, in the case of Bogotá, a particularly favorable combination of relative climate conditions and market size. However, rather than interpreting these results as a direct recommendation for location, they should be understood as an indication that both cities concentrate territorial conditions that yield a high and stable position under different weighting schemes. This distinction is important because it prevents an overly simplistic reading of the ranking and preserves the index's comparative nature.

The rise of Barranquilla in the large-scale scenario constitutes one of the most relevant findings of the study. Unlike the small- and medium-scale scenarios—where the combination of connectivity and market size more clearly favors Andean cities—the large-scale configuration assigns greater weight to energy support and territorial risk. Under this structure, Barranquilla improves substantially in relative terms. This result aligns with the literature suggesting that the criteria relevant for large-scale facilities are not necessarily the same as those for smaller infrastructures (Arzumanyan *et al.*, 2025; Turek & Radgen, 2021). It also suggests that, in the Colombian case, a large-scale data center siting strategy may not fully coincide with the dominant urban geography defined by market size or digital centrality.

Another important result is that the large-scale scenario not only modifies specific positions but also introduces the greatest degree of differentiation relative to the

small- and medium-scale scenarios. Sensitivity and rank concordance analyses show that small- and medium-scale scenarios remain very close to each other, while the large-scale scenario produces more pronounced shifts across several cities. From a methodological standpoint, this supports the need to avoid relying on a single weighting scheme when discussing data center location without explicitly distinguishing the functional scale. From an applied perspective, it suggests that policy and planning discussions on digital infrastructure in Colombia should more clearly differentiate between local or regional-scale projects and large-scale developments, whose territorial logic may differ substantially.

The observed robustness in the leadership of Bogotá and Medellín, along with the overall stability of rankings, provides an additional methodological insight. Although the model relies on deliberate simplifications and proxies, the overall ordering does not change erratically under reasonable perturbations to weights. This does not imply that the index is independent of modeling choices, but it does suggest that the overall hierarchy is not driven solely by arbitrary parameterization. In multicriteria territorial screening studies, this property is particularly valuable, as it helps distinguish fragile outcomes from patterns that persist under controlled variations in the weighting scheme.

At the same time, the findings should be interpreted in light of the scope and simplifications of the study. First, the analysis operates at the city level rather than the site level and therefore does not aim to replace microlocation assessments, engineering studies, or detailed site-

specific analyses. Second, the energy dimension is represented through proxies of the electrical environment and functional proximity to the transmission system, which provide a useful approximation for inter-urban screening but do not directly measure available capacity, service quality, or marginal connection costs. Third, the territorial risk dimension is limited to the seismic component. At the same time, other potentially relevant factors for real-world investment decisions—such as physical asset security, local conflict dynamics, or more specific regulatory constraints—are excluded due to the lack of a homogeneous, comparable operational formulation across cities.

An additional limitation is the lack of exact temporal alignment across data sources. The model integrates official data from different years and reference periods, reflecting the actual structure of data availability in Colombia rather than a discretionary assembly decision. Although this introduces a temporal synchronization limitation, its expected impact is moderate, given the comparative and inter-urban nature of the analysis and the relatively stable or slowly changing nature of several variables considered. Accordingly, the results should be interpreted as a territorial screening approximation based on the best available comparable official data, rather than as a perfectly synchronized snapshot of all dimensions.

The findings also have implications for public policy. As digital infrastructure gains increasing relevance in Colombia, decisions regarding territorial prioritization and data center promotion would benefit from explicit, comparable, and technically transparent evaluation frameworks. In this

sense, the results suggest that general narratives of innovation or digital transformation may be insufficient, on their own, to support territorially consistent infrastructure decisions when sustainability-related criteria are expected to play a central role.

Ultimately, the main contribution of this study is not the identification of a single “winning” city, but rather the demonstration that the territorial suitability of Colombian cities for hosting data centers varies according to project scale and the combination of criteria considered. While methodologically modest, this conclusion carries relevant implications for urban planning, digital policy, and future research. It also opens the door to subsequent studies that refine the analysis at finer spatial scales, incorporate additional territorial layers, and further validate against real-world projects or observed locations.

6. CONCLUSIONS

This study proposed a multicriteria evaluation framework to compare the relative suitability of ten Colombian cities as candidate locations for data centers across three scale scenarios. The results show that territorial suitability is not uniform across cities and that its behavior depends on the functional scale of the project. In all three scenarios analyzed, Bogotá and Medellín ranked first and second, respectively, while Barranquilla showed a clear improvement in relative performance under the *large-scale* scenario, confirming that relevant location criteria shift as the importance of energy support and territorial risk increases.

From a methodological standpoint, the study provides a reproducible inter-urban screening tool based on official, open data sources, suitable for contexts where detailed site-level information or private operational data are not readily available. The use of a synthetic index—combined with differentiated weighting scenarios, local and global sensitivity analyses, and rank concordance tests—enabled the construction of an interpretable ranking with sufficient robustness to support preliminary comparisons across cities. In this sense, the main contribution of the study is not the identification of a definitive location, but rather the provision of a transparent analytical basis for discussing urban alternatives in a more structured and territorially sustainable manner.

The findings also carry practical implications for territorial planning, energy sustainability, and digital policy in Colombia. If decisions regarding large-scale digital infrastructure are to be technically consistent, they should be supported by explicit comparative evaluations rather than relying solely on general narratives of innovation or urban centrality. At the same time, results should be interpreted within the limits of the study: the model operates at the city level, relies on proxies to represent the energy environment, restricts territorial risk to the seismic component, and does not incorporate additional contextual variables such as physical asset security, localized conflict dynamics, or site-specific regulatory conditions.

Building on these considerations, future research could extend this framework in at least four concrete directions: incorporating finer spatial scales, integrating additional

territorial or regulatory layers, validating the index against real-world projects or observed location decisions, and developing microlocation analyses for cities with stronger relative performance. This work provides an initial empirical approximation to the problem of inter-urban data center location in Colombia and opens a research agenda on digital infrastructure, territory, and territorial sustainability.

7. REFERENCES

- Arzumanyan, M., Edna Rodriguez Calzado, Ning Lin, Vaibhav Bahadur, Jani Das, Tingwei Lucy Ko, & Lars Koesterke. (2025). Geospatial suitability analysis for data center placement: A case study in Texas, USA. *Sustainable Cities and Society*, 131, 106687. <https://doi.org/10.1016/j.scs.2025.106687>
- Covas, M. T., Silva, C. A., & Dias, L. C. (2013). On locating sustainable Data Centers in Portugal: Problem structuring and GIS-based analysis. *Sustainable Computing: Informatics and Systems*, 3(1), 27-35. <https://doi.org/10.1016/j.suscom.2012.12.001>
- Departamento Administrativo Nacional de Estadística (DANE). (2025a). Consulta DIVIPOLA y tabla de cabeceras municipales y centros poblados. <https://geoportal.dane.gov.co/geovisores/territorio/consulta-divipola-division-politico-administrativa-de-colombia/>
- Departamento Administrativo Nacional de Estadística (DANE). (2025b). Proyecciones y retroproyecciones de población municipal para el periodo 1985–2017 y 2018–2042 con base en el CNPV 2018. <https://www.dane.gov.co/index.php/esta>

- disticas-por-tema-2/demografia-y-poblacion/proyecciones-de-poblacion
- Electric Power Research Institute (EPRI). (2024). Data Centers: Power Demand Flexibility and Impacts on the Electric Sector. Electric Power Research Institute. <https://restservice.epri.com/publicdownload/000000003002030444/0/Product>
- Hoosain, M. S., Paul, B. S., Kass, S., & Ramakrishna, S. (2023). Tools Towards the Sustainability and Circularity of Data Centers. *Circular Economy and Sustainability*, 3, 173-197. <https://doi.org/10.1007/s43615-022-00191-9>
- Hussain, S. N., Al-Mandhari, M., Ali, S. M. F., Zaib, A., & Ghosh, A. (2026). GIS-Driven Regional Assessment for Sustainable Data Center Siting in the United Kingdom. *Land*, 15(3), 516. <https://doi.org/10.3390/land15030516>
- Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). (2024). Normales climatológicas. <https://www.datos.gov.co/api/views/nsz2-kzccq>
- Jerléus, K., Ibrahim, G., & Augustsson, A. (2024). Environmental footprints of the data center service sector in Sweden. *Heliyon*, 10, e31290. <https://doi.org/10.1016/j.heliyon.2024.e31290>
- Kheybari, S., Davoodi Monfared, M., Farazmand, H., & Rezaei, J. (2020). Sustainable Location Selection of Data Centers: Developing a Multi-Criteria Set-Covering Decision-Making Methodology. *International Journal of Information Technology & Decision Making*. <https://doi.org/10.1142/S021962202020500157>
- Koot, M., & Wijnhoven, A. B. J. M. (2021). Usage impact on data center electricity needs: A system dynamic forecasting model. *Applied Energy*, 291, 116798. <https://doi.org/10.1016/j.apenergy.2021.116798>
- Ministerio de Tecnologías de la Información y las Comunicaciones (MinTIC). (2023). Internet fijo. <https://www.datos.gov.co/api/views/n48w-gutb>
- Murino, T., Monaco, R., Nielsen, P. S., Liu, X., Esposito, G., & Scognamiglio, C. (2023). Sustainable Energy Data Centres: A Holistic Conceptual Framework for Design and Operations. *Energies*, 16(15), 5764. <https://doi.org/10.3390/en16155764>
- National Renewable Energy Laboratory (NREL). (2024). Small-Scale Data Centers for Grid-Interactive Efficient Buildings. National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy24osti/90734.pdf>
- Newkirk, A. C., Hanus, N., & Payne, C. T. (2024). Expert and operator perspectives on barriers to energy efficiency in data centers. *Energy Efficiency*, 17(6), 63. <https://doi.org/10.1007/s12053-024-10244-7>
- Oztas, S. (2025). Harnessing High-Altitude Advantages: Sustainable Data Center Site Selection in Ski Resort Regions for Optimized Energy Efficiency. *Sustainability*, 17(8), 3494. <https://doi.org/10.3390/su17083494>
- Servicio Geológico Colombiano (SGC). (2024). Amenaza sísmica municipal y sistema de consulta del modelo nacional de amenaza sísmica de Colombia. <https://www2.sgc.gov.co/ProgramasDel>

investigacion/geoamenazas/Paginas/amenaza-sismica.aspx

es%20Mensuales/2025/03_Marzo/00_General_Mercado_03_2025.pdf

Shuja, J., Bilal, K., Madani, S. A., Othman, M., Ranjan, R., Balaji, P., & Khan, S. U. (2016). Survey of Techniques and Architectures for Designing Energy-Efficient Data Centers. *IEEE Systems Journal*, 10(2), 507-519. <https://doi.org/10.1109/JSYST.2014.2315823>

Turek, D., & Radgen, P. (2021). Optimized data center site selection—Mesoclimatic effects on data center energy consumption and costs. *Energy Efficiency*. <https://doi.org/10.1007/s12053-021-09947-y>

Unidad de Planeación Minero Energética (UPME). (2025). Habilitantes socioambientales para el análisis de infraestructura energética: Resumen de conexiones de subestaciones del STR al STN para ciudades principales. <https://www.upme.gov.co/proyectos-de-inversion/enfoque-territorial/>

XM S.A. E.S.P. (2025). Informe General del Mercado, marzo de 2025. <https://sinergox.xm.com.co/infms/Inform>