Revista
Ciencia e Ingeniería Neogranadina
2025 julio - diciembre
Vol. 35(2) ISSN: 0124-8170 · e-ISSN: 1909-7735 ■ pp. 141-160

Editorial Neogranadina

**DOI:** https://doi.org/10.18359/rcin.7763



# Determinant Factors in Estimating Charging Stations for Electric Vehicles in Bogotá Using Voronoi Regions*

Jaime Francisco Pantoja Benavides[a] ■ Diego Julián Rodríguez Patarroyo[b] ■ Julián Andrés Salamanca Bernal[c]

**Abstract:** This study presents a methodological model for planning the locations of electric vehicle (EV) charging stations in Bogotá, using spatial statistical methods and tools that analyze the variables influencing such planning. The research focuses on dividing the city into zones based on the 37 EV charging stations active as of February 2024, applying the Voronoi polygon theory. Data on population, road networks, and mobility patterns within each zone were collected to create maps and conduct detailed analysis. The results indicate that the current distribution of charging stations follows identifiable spatial patterns, allowing trends in their placement to be observed. These insights support the formulation of strategic plans to optimize station distribution and help estimate the resources needed to develop an efficient electric mobility infrastructure in the city.

**Keywords:** Charging Stations; Electric Vehicles; Voronoi zones

**Recibido:** 03/02/2025 **Aceptado:** 27/06/2025 **Disponible en linea**: 22/10/2025

**How to cite:** J. F. Pantoja Benavidez, D. J. Rodríguez Patarroyo, y J. A. Salamanca Bernal, «Determinant Factors in Estimating Charging Stations for Electric Vehicles in Bogotá Using Voronoi Regions», Cien. Ing.Neogranadina, vol. 35, n.º 2, pp. 141–160, oct. 2025.

* Research Article

a Master of Engineering, Associate Professor. Universidad Distrital Francisco José de Caldas, Faculty of Technology, Research Group Laboratory of Alternative Energy Sources LIFAE, Bogotá, Colombia. Email: jfpantojab@udistrital.edu.co; ORCID: https://orcid.org/0000-0003-0107-9542

b Doctor in Engenieering. Full Professor. Universidad Distrital Francisco José de Caldas, Faculty of Engineering, Research Group Laboratory of Alternative Energy Sources LIFAE, Bogotá, Colombia. Email: djrodriguezp@udistrital.edu.co; ORCID: https://orcid.org/0000-0002-4907-5674

c Doctor un Applied Physics. Full Professor. Universidad Distrital Francisco José de Caldas Faculty of Sciences and Education, Physics and Informatics Research Group FISINFOR, Bogotá, Colombia. Email: jasalamanca@udistrital.edu.co; ORCID: https://orcid.org/0000-0001-8378-4215

## *Factores determinantes en la estimación de estaciones de carga para vehículos eléctricos en Bogotá, utilizando Regiones de Voronoi*

**Resumen:** Este estudio presenta un modelo metodológico para planificar ubicaciones de estaciones de carga de vehículos eléctricos en Bogotá donde se hace uso de métodos y herramientas de la estadística espacial de variables estadísticas que influyen en dicha planificación. El estudio se centra en dividir la ciudad en zonas según las 37 estaciones de carga para vehículos eléctricos (VE) activas hasta febrero de 2024 utilizando la teoría de polígonos de Voronoi. La información recopilada para el estudio sobre la población, infraestructura vial y la movilidad de cada zona permite elaborar mapas y poder así analizar la información. Los resultados del estudio muestran que la distribución actual de las estaciones de carga sigue ciertos patrones, lo que permite identificar tendencias en su ubicación. Esto facilita la formulación de planes y estrategias para mejorar su distribución, así como la proyección de los recursos necesarios para el desarrollo de una infraestructura de movilidad eléctrica eficiente en la ciudad.

**Palabras clave:** estaciones de carga; vehículos eléctricos; zonas de voronoi

## *Fatores Determinantes na Estimativa de Estações de Recarga para Veículos Elétricos em Bogotá Utilizando Regiões de Voronoi*

**Resumo:** Este estudo apresenta um modelo metodológico para planejar a localização de estações de recarga de veículos elétricos em Bogotá, fazendo uso de métodos e ferramentas da estatística espacial de variáveis estatísticas que influenciam esse planejamento. O estudo concentra-se em dividir a cidade em zonas a partir das 37 estações de recarga para veículos elétricos (VE) ativas até fevereiro de 2024, utilizando a teoria dos polígonos de Voronoi. As informações coletadas para o estudo sobre a população, a infraestrutura viária e a mobilidade de cada zona permitem elaborar mapas e, assim, analisar os dados. Os resultados do estudo mostram que a distribuição atual das estações de recarga segue certos padrões, o que permite identificar tendências em sua localização. Isso facilita a formulação de planos e estratégias para melhorar sua distribuição, bem como a projeção dos recursos necessários para o desenvolvimento de uma infraestrutura de mobilidade elétrica eficiente na cidade.

**Palavras-chave:** estações de recarga; veículos elétricos; regiões de Voronoi

## Introduction

To address the challenges posed by complex urban planning, geostatistical approaches—along with tools such as Geographic Information Systems (GIS)—have become essential over the past decade [1]–[3]. By considering key factors such as population density, traffic patterns, and the socioeconomic composition of metropolitan areas, these approaches have enabled the optimization of vital infrastructure, including electric vehicle (EV) charging stations. In urban zones, where access to infrastructure and services poses significant challenges, the application of spatial analytic methods and optimization algorithms has proven particularly effective. These methods support sustainability goals by integrating dynamic data and localized solutions based on mobility needs, while also facilitating more equitable and effective planning.

This study employs a spatial analytic approach using Voronoi tessellation to identify the key parameters that influence the placement of EV charging stations in metropolitan areas. The research aims to gain a comprehensive understanding of how socioeconomic status, station distribution, and existing infrastructure interact. Additionally, it provides a solid framework for incorporating EV charging stations into urban planning in a way that maximizes accessibility and reduces disparities. By addressing the demands of modern electric mobility, this strategy contributes to a more equitable and sustainable model of urban development—one that aligns with the socioeconomic and environmental challenges facing contemporary cities.

Due to their infrastructure and greater economic potential, higher-income areas tend to have a greater concentration of charging stations [4]. Conversely, regions with lower socioeconomic status often lack such infrastructure due to budgetary limitations and insufficient development. In socioeconomic sectors classified as strata 4, 5, and 6, the early installation of charging stations serves as a model for EV adoption. However, to ensure long-term, equitable, and sustainable development, it is essential to expand this infrastructure into less affluent communities. Furthermore, incorporating renewable energy sources into the design of charging stations can optimize energy use and advance environmental goals, supporting the fair and efficient distribution of infrastructure citywide [5], [6].

The installation of EV charging stations can significantly alter local energy demand, thereby impacting utility pricing policies and economic models [7]. These shifts may lead to increased energy consumption peaks, potentially overloading distribution lines and transformers, reducing their service life, and causing power quality issues such as voltage fluctuations or electrical distortions. However, when integrated with Vehicle-to-Grid (V2G) technologies, charging stations can function as active distributed energy storage resources. This allows vehicles to return energy to the grid during peak demand, enhancing system stability and reducing operating costs [8].

Although several objectives drive the optimization of EV charging station placement, the primary goal remains improving infrastructure quality and user experience [9]. Locating stations in high-demand residential and commercial areas enhances convenience and accessibility, encouraging EV adoption by alleviating range anxiety. Strategic site selection also enables economic integration with the existing electrical grid, significantly reducing infrastructure costs [10].

To maximize grid efficiency and prevent overload, charging station placement must be planned in conjunction with energy storage systems designed to manage demand peaks. Clean energy use is more effective when stations are positioned near sustainable energy sources. Integrating this infrastructure with traffic control and broader urban planning efforts improves city logistics and accelerates the shift toward smart, renewable-energy-powered cities. This approach aligns with global sustainability objectives, including those outlined by the United Nations, particularly the reduction of greenhouse gas emissions [11].

A variety of strategies have been proposed to optimize EV charging station locations within the context of gradual infrastructure expansion [12] . Optimization and machine learning techniques are central to these strategies. The placement problem is framed as a facility location problem using a node-based approach, in which the optimal site is selected from among candidate locations based on demand patterns. Due to the NP-hard nature of the problem, heuristic methods are often employed [13]. Additionally, route-based and trip-based approaches place stations along high-traffic roads or common travel routes, accounting for traffic flow and driver behavior [14].

Another proposed method is the Maximum Coverage Location Model (MCLM), which seeks to position facilities in a way that covers the greatest number of demand points within a critical distance [15]. Meanwhile, the Set Covering Location Model (SCLM) aims to minimize the number of facilities required to cover all demand points, regardless of their individual demand levels. The P-median model, on the other hand, minimizes the total travel cost between facilities and demand points. Approaches based on Voronoi zones and k-means clustering are also included in this category [16].

These approaches are evaluated based on multiple criteria, including cost reduction, demand coverage, and power grid efficiency. Factors such as geographic location, traffic density, data availability, and the objectives of infrastructure providers and urban planners also influence the choice of the most appropriate model.

However, Bogotá faces significant challenges in transitioning to electric mobility due to marked disparities in socioeconomic status and urban infrastructure. While the northern sectors of the city benefit from better road networks, higher economic activity, and greater readiness to adopt clean technologies, the southern and peripheral zones lack adequate infrastructure and accessibility. These inequalities not only affect the distribution of charging stations but also hinder EV adoption in lower-income communities. Achieving a fair transition to electric mobility requires inclusive urban planning policies, economic incentives, and the integration of renewable energy sources.

To optimize station siting, this study proposes the use of spatial analysis and optimization models—specifically segmentation through Voronoi zones. These models help identify the best locations for expanding EV charging infrastructure by maximizing coverage and accessibility while minimizing strain on the existing electrical grid. Strategic siting includes both residential areas with high EV adoption potential and zones with high vehicle density.

By applying geospatial technologies to enhance EV charging infrastructure placement, this study contributes to both urban planning and the advancement of electromobility. The integration of spatial analysis tools—such as Voronoi diagrams—with GIS and optimization methods allows for more effective planning and evaluation of existing infrastructure. This approach reduces disparities in access to clean mobility and supports the integration of renewable energy sources. The resulting analytical framework can be adapted for use in other cities with similar urban characteristics.

The structure of this article begins with an introduction that contextualizes the importance of EV charging infrastructure. The theoretical framework outlines the principles of spatial analysis using Voronoi regions, highlighting their relevance for planning. The methodology section details the variables used, their spatial representation, and the segmentation process implemented through Python-based tools.

## Theoretical Framework

This study utilized data from various official sources, including the National Administrative Department of Statistics (DANE) and open-access platforms such as OpenStreetMap. Data processing and analysis were carried out using tools developed in the Python programming language. The dataset encompassed demographic, mobility, and infrastructure-related variables. An exploratory data analysis was conducted to identify trends and potential discrepancies, ensuring a solid foundation for subsequent modeling.

To guarantee data quality, a thorough cleansing and preprocessing procedure was implemented. Once refined, the data was integrated using QGIS to produce geographic layers and conduct in-depth spatial analyses, including the generation of thematic maps and Voronoi diagrams. This allowed for a comprehensive and visually enriched understanding of the georeferenced data related to the strategic placement of EV charging stations in Bogotá D.C.

The dataset included variables such as EV demand, demographics, socioeconomic status, points of interest, parking density, land use, and distances to the central business district (CBD). Following data collection, a space-time distribution analysis was performed to assess how charging demand varies across time and geographic space, helping to identify areas and periods of high or low demand.

Charging demand was further categorized using a clustering algorithm based on socioeconomic status and population density, enabling the definition of distinct zones. This method is adaptable to the natural distribution of demand and does not require a predetermined number of zones. It supports the identification of high- and low-demand areas, which in turn can guide subsequent spatial segmentation.

The study area was partitioned into irregular polygons through a Voronoi diagram. Each polygon is centered on a cluster point, and every location within a polygon is closer to its respective center than to any other point. This spatial division more accurately captures the variations in charging demand across the city.

## Voronoi Diagrams

In the field of urban planning, the use of Voronoi diagrams facilitates the delineation of geographic regions based on proximity to electric vehicle (EV) charging stations. As demand for EVs continues to grow, the integration of Voronoi diagrams with Geographic Information Systems (GIS) and mobility data supports the development of effective policies for expanding charging infrastructure [17]. Typically, the spatial distribution of charging stations is irregular, leading to areas of influence that vary in size and coverage. As a result, this irregularity impacts the overall efficiency and equity of the network's coverage.

## Voronoi Regions

Voronoi diagrams are one of the simplest interpolation methods based on Euclidean space, generating geometric constructions that partition a plane into regions. Each region corresponds to one point in a finite set and includes all locations closer to that point than to any other. These partitions enable the division of the plane into as many regions as there are points, forming a computational geometry structure that stores information about spatial proximity and relationships between points. For a finite collection of points in the plane, the Voronoi diagram provides a clear and efficient way to model influence zones and spatial adjacency. $P = \{p_1, p_2, p_3, ...p_k\}$ with $k \geq 2$, where each $p_i$ is associated with the points of the plane that are closer or equal to $p_j$ that of any other point with $i \neq j$ for $i, j = 1, 2, 3, ..., k$, the regions formed by proximity neighborhoods are known as Voronoi regions or Voronoi polygons. They are also referred to as Thiessen polygons, named after the American meteorologist Alfred H. Thiessen, who used them in 1911 to predict weather patterns [18]–[21].

Euclidean distance: Let $p_i = (x_i, y_i)$ and $p_j = (x_j, y_j)$ be any two points in the plane $R^2$, the Euclidean distance between the points is given by equation (1).

$$d_{p_i p_j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \tag{1}$$

With,

1) The distance between $p_i$ and $p_j$ is positive.
2) The distance between $p_i$ and $p_j$ is the same between $p_j$ and $p_i$.
3) If the distance between $p_i$ and $p_j$ is zero, then $p_i$ and $p_i = p_j$.
4) If $p_k$ is non-collinear, then, $d_{p_i p_j} \leq d_{p_i p_k} + d_{p_k p_j}$

Voronoi diagram, noted as $V(p_i)$ It is generated by subdividing the plane into $n$ regions—equal to the number of points—based on the proximity criterion described in Equation (2).

$$V(p_i) = \left\{ x \subseteq \Re^2 \;\; / \;\; d(x, p_i) \leq d(x, p_j) \right\},$$
$$\text{for } i \neq j \tag{2}$$

The region $V(p_i)$ consists of all points x belonging to $R^2$ for which $p_i$ Each region represents the area of the nearest neighbor. It is polygonal, convex, and bounded, formed by the intersection of half-planes defined by the perpendicular bisectors between adjacent points. $k-1$ The region is composed of half-planes. There are various algorithms available to construct Voronoi regions; below is a simple and clear explanation of how Voronoi regions are formed for two and three points in the plane.

For the case of two points, the Voronoi region is formed by first drawing a straight line connecting the two points. Then, the perpendicular bisector of that line is constructed. This bisector serves as the boundary that divides the plane into two regions, each containing all the points closer to one of the original points than to the other $p_1$ to the point $p_2$ and then a perpendicular line is drawn to the straight line segment $\overline{p_1p_2}$ at its midpoint called the mediatrix, which divides the plane into two regions $V(p_1)$ and $V(p_2)$ , the region $p_1$ contains all the points x such that the distance $d(x, p_1) \leq d(x, p_2)$, its representation is shown in Figure 1. Left.

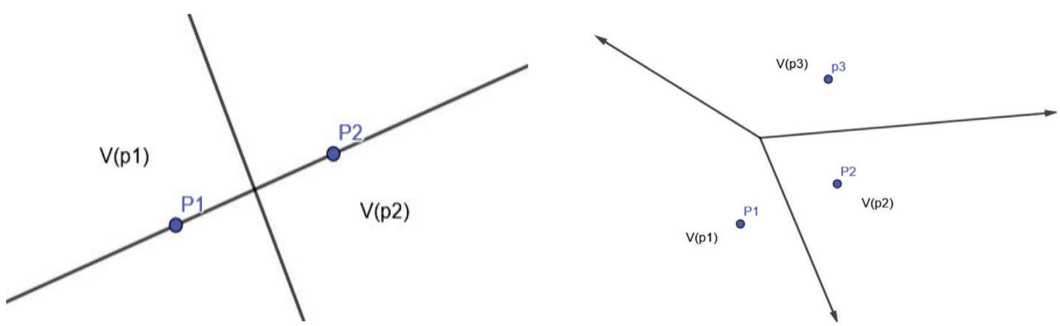
Now let, $p_1$, $p_2$ and $p_3$ Let $\mathbf{P_1}$, $\mathbf{P_2}$, and $\mathbf{P_3}$ be points on the plane. Following the same reasoning used for Voronoi regions with two points, the plane is now divided into three regions—each corresponding to one of the points—forming three Voronoi regions. The process follows this sequence:

1) Line segments are drawn between each pair of points
2) $\overline{p_1p_2}$ , $\overline{p_1p_3}$ and $\overline{p_2p_3}$
3) The midpoints of each segment are determined.
4) Perpendicular bisectors are drawn at each midpoint.
5) The intersection point of the three bisectors, known as the circumcenter, is identified.
6) Finally, from the circumcenter, the bisectors are extended, dividing the plane into three Voronoi regions.

The results are illustrated in Figure 1 (right), where the three Voronoi regions are shown clearly.

$V(p_1)$, $V(p_2)$ and $V(p_3)$, where for each $x \in V(p_1)$, the distance $d_{x,p_1} \leq d_{x,p_2}$ and $d_{x,p_1} \leq d_{x,p_3}$.

**Figure 1.** Voronoi regions for 2 and 3 points




**Source:** Own elaboration.

## Methods

This section presents an overview of the Planning Zone Units (UPZs), which are designated areas aimed at facilitating the management and planning of urban development within the city. It also offers an in-depth analysis of the socioeconomic classification of nuclear families in Bogotá, based on comprehensive official surveys that provide insights into labor market conditions, living standards, and the economic characteristics of households.

The study considers variables such as the number of automobiles, parking lots, health centers, universities, fuel stations, shopping centers, supermarkets, parks, and more. Finally, the current infrastructure of EV charging stations in Bogotá D.C., Colombia, is described, including the companies that operate them and the supported vehicle brands. This information is essential for understanding the spatial distribution and demand for charging stations across the city and for strategically planning their future expansion.

## Planning Zone Units

The concept of Planning Zone Units (UPZs) in Bogotá, D.C., Colombia, was established under Decree 190 of 2004, prior to the implementation of the Land Use Plan (POT) 2022–2035 for territorial planning. UPZs are defined areas within the city, created to enhance the management and organization of urban development.

## Socioeconomic Level

The socioeconomic status of nuclear families in Bogotá is primarily determined using two key data sources: the Large Integrated Household Survey (GEIH, Gran Encuesta Integrada de Hogares) and the National Quality of Life Survey (ENCV, Encuesta Nacional de Calidad de Vida), both conducted by the National Administrative Department of Statistics (DANE). These surveys provide comprehensive data on labor market dynamics and living conditions, including housing, access to public services, education, health, income, and other economic indicators relevant to the assessment of family well-being.

Although there is no universally accepted model for determining socioeconomic status, it is generally estimated based on a set of key variables such as household income, educational attainment, unemployment rate, access to basic services, housing quality, and the number of people per bedroom. These indicators help estimate the economic capacity and overall well-being of nuclear families.

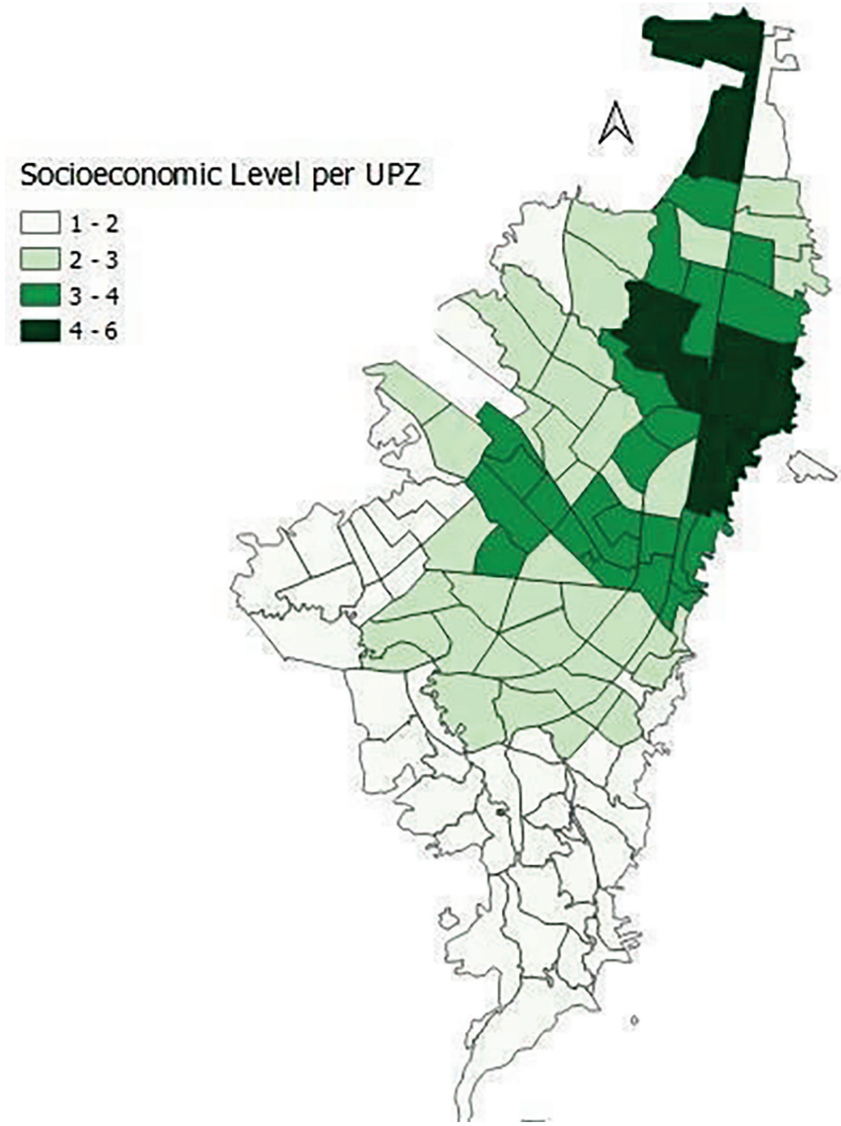
In Bogotá, socioeconomic classification is primarily carried out through the urban socioeconomic stratification system, which is used to determine differential rates for public services based on a household's ability to pay [22]. This system is divided into six strata: Stratum 1 represents the most vulnerable areas, while Stratum 6 corresponds to areas with the highest socioeconomic conditions. Figure 2, illustrates the geographical distribution of socioeconomic strata across the city, organized by UPZs.

## Charging Stations or Electrolineras

The current operational charging stations in Bogotá are managed by private companies such as ENEL X, Autogermana, Wallbox Colombia, Arco Energy, and Dielco Electric Systems. These companies provide chargers compatible with a wide range of electric vehicle brands and standards, including BYD, European Type 2 Standard, JAC, DONFENG, JMC Chinese Standard, Renault, BMW, Volvo, Porsche, Jaguar, Mitsubishi, Nissan, Mercedes-Benz, and Changan (ENEL [23]).

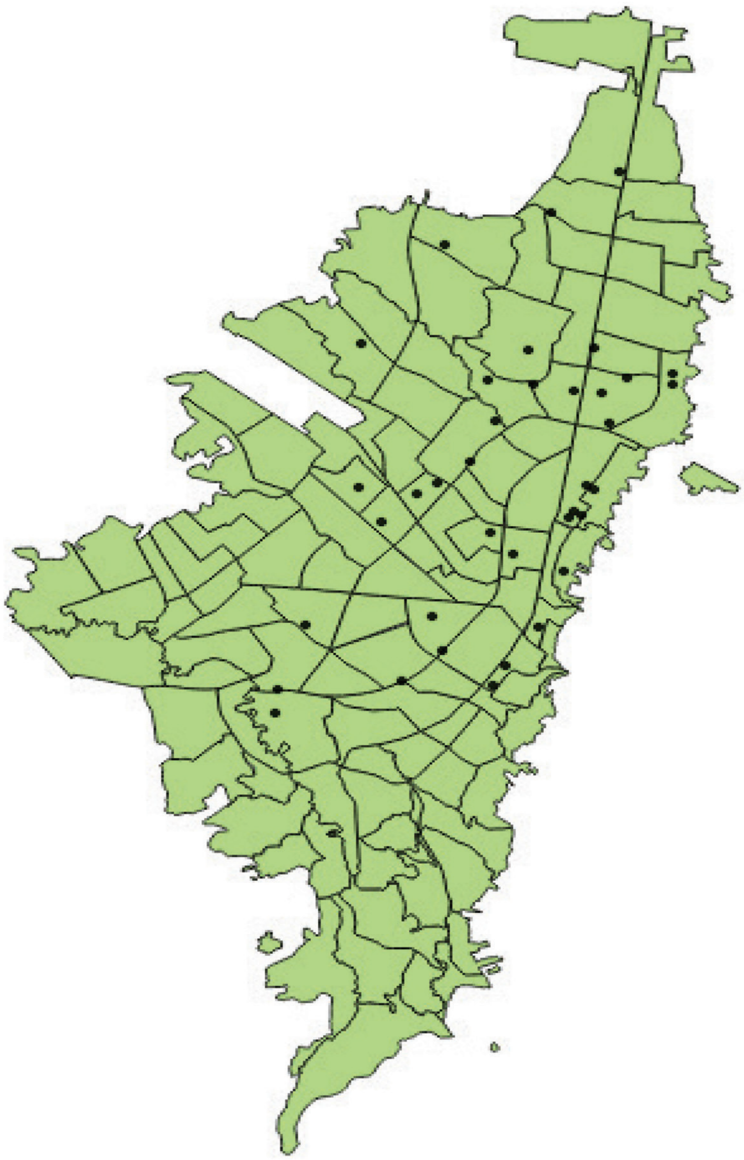
In this study, a total of 37 operational charging stations (*electrolineras*) in Bogotá D.C. were selected as of February 2024, based on publicly available information from platforms such as Electromaps, ENEL X, Terpel, Dielco, and Celsia [24]- [27]. Their geographic distribution is illustrated in Figure 3.

**Figure 2.** Geographic Distribution of Socioeconomic Levels in Bogotá D.C., Colombia, Organized by UPZs




**Source:** Own elaboration.

**Figure 3.** Operational charging stations in Bogotá D.C., Colombia



**Source:** Own elaboration.

## Infrastructure and Other Variables

In terms of infrastructure, the collected information includes a total of 10 variables, each with 111 records corresponding to the Planning Zone Units (UPZs) in 19 of the 20 localities of Bogotá. The locality of Sumapaz was excluded from the study due to its entirely rural character and minimal impact on vehicle use. Similarly, UPZ 117, which corresponds to the airport zone unit, was excluded because of its unique mobility patterns, demographics, and infrastructure characteristics [28]

The variables considered in the study are outlined in Table 1. Although the data used were derived from a case study of Bogotá, D.C., Colombia, the methodology presented is not limited to this specific context and may be applied to any urban area. It is important to note that most cities are politically divided into administrative zones, and factors such as socioeconomic levels are typically measured using graduated classification systems. Therefore, the methodological approach described in this article is scalable and adaptable to other urban contexts that share similar characteristics.

**Table 1.** List of variables used: demographic (DEM), mobility (MOV) and infrastructure (INFR)

| Variables | Type | Source |
|---|---|---|
| socioeconomic level | DEM | [29] |
| # family nucleus | DEM | [30] |
| # Automobiles | MOV | [31] |
| # parking | INFR | [32] |
| # health centers | INFR | [32],[33] |
| # universities | INFR | [32],[33] |
| # fuel stations | INFR | [32],[33] |
| # commercial centers | INFR | [32],[33] |
| # supermarket | INFR | [32],[33] |
| # parks | INFR | [32],[33] |

**Source:** Own elaboration.

## Procedure

The generation of Voronoi regions using the 37 active charging stations in the city of Bogotá D.C., Colombia, was carried out using Python version 3.10.6 on the Linux Ubuntu platform. The process employed the Visual Studio Code environment along with specific tools from QGIS version 3.28.9-Firenze, under the GNU Public License [34].

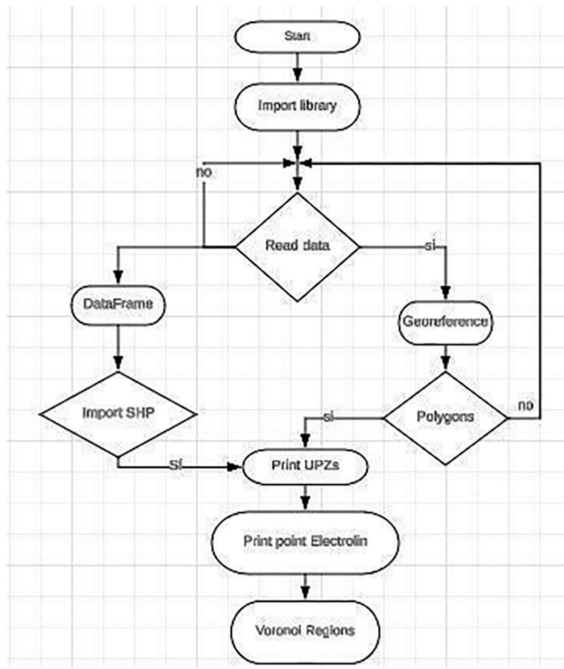
Figure 4 presents a flowchart summarizing and illustrating the procedure used to construct the Voronoi regions. Additionally, the methodology developed in QGIS is detailed, including the loading of polygon layers of Bogotá and the point data representing the charging stations.

To load the spatial layers into QGIS, the following sequence is used:

- Navigate to "Layer / Add Layer / Add Vector Layer" to incorporate shapefiles or other vector formats (Buzari, [35]),
- Then select "Layer / Add Layer / Add Delimited Text Layer" to load CSV or TXT files containing spatial point data (Buzari, [35]).

This ensures the spatial alignment of the charging stations within their geographic context, as visualized previously in Figure 3.

**Figure 4.** Flowchart for Voronoi regions




**Source:** Own elaboration.

## Results

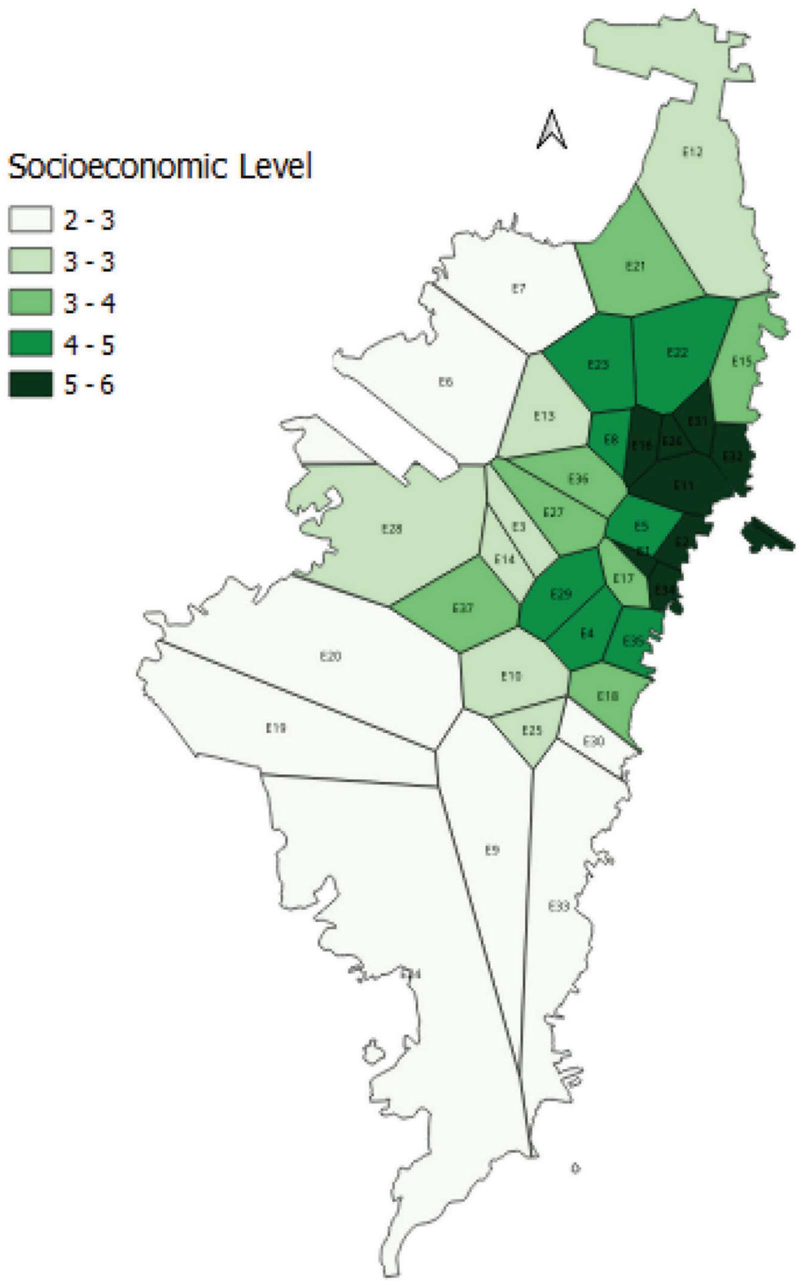
This study conducts a geographic analysis using Voronoi regions, with Bogotá D.C., Colombia as the focal point. The analysis incorporates variables such as the distribution of nuclear families, socioeconomic levels, and the existing infrastructure in the city, offering a comprehensive understanding of the location and accessibility of electric vehicle (EV) charging stations.

The Voronoi polygon layer, generated for each point in the input dataset (i.e., the EV charging stations), is shown in Figure 5. This figure illustrates the geographic areas of influence associated with each charging station.

A visual inspection of Figure 6, reveals that the smallest Voronoi regions are located in the central and northern urban areas, where the concentration of EV charging stations is highest. Conversely, the larger Voronoi regions, found in the southern zones and on the periphery of the city, correspond to areas with fewer charging stations.

After segmenting the city into Voronoi geographic regions, thematic maps are developed to analyze the relationship between the spatial distribution of EV charging stations and several contextual factors, including socioeconomic status, household distribution, and the organization of urban infrastructure.

**Figure 5.** Average socioeconomic level by Voronoi regions




**Source:** Own elaboration.

Figure 5 illustrates the distribution and trends in socioeconomic levels across Bogotá. The data reveal that approximately 38% of the population belongs to level 3, while levels 5 and 6 collectively represent 27% of the total population.

Socioeconomic level 3, often associated with the middle class, includes neighborhoods located at a considerable distance from the city center. These areas offer moderate urban amenities and reflect a stable income, though not sufficient for luxury expenditures. Common sources of income in this category include private companies, administrative roles, skilled trades, and public sector jobs.

In contrast, socioeconomic levels 5 and 6—the highest strata—are less common but represent the most economically stable segments of the population. Individuals in these strata have higher incomes, allowing them to afford better housing, full access to urban amenities, and the economic means to purchase electric vehicles. In the map, these areas are marked in dark green.

The main EV charging stations located in these higher socioeconomic areas include EUnicentro (E31), ECtaxis (E26), CityCharging (E11), and EPHermanos (E32), all situated within the locality of Usaquén. In the northern sector of Bogotá, high socioeconomic levels are found in UPZs such as Santa Bárbara, Chicó Lago, Usaquén, and Country Club. Neighboring UPZs like La Alhambra, El Prado, Los Andes, and El Refugio correspond to levels 4 and 5.

Conversely, the southern sector of the city is predominantly characterized by socioeconomic levels 1, 2, and 3. In terms of urban infrastructure, the northern sector stands out for its superior and wider road networks, which contribute to enhanced mobility, accessibility, and an overall better quality of life for its residents.

A summary of this information is provided in Table 2.

**Table 2.** Socioeconomic and Infrastructure Distribution

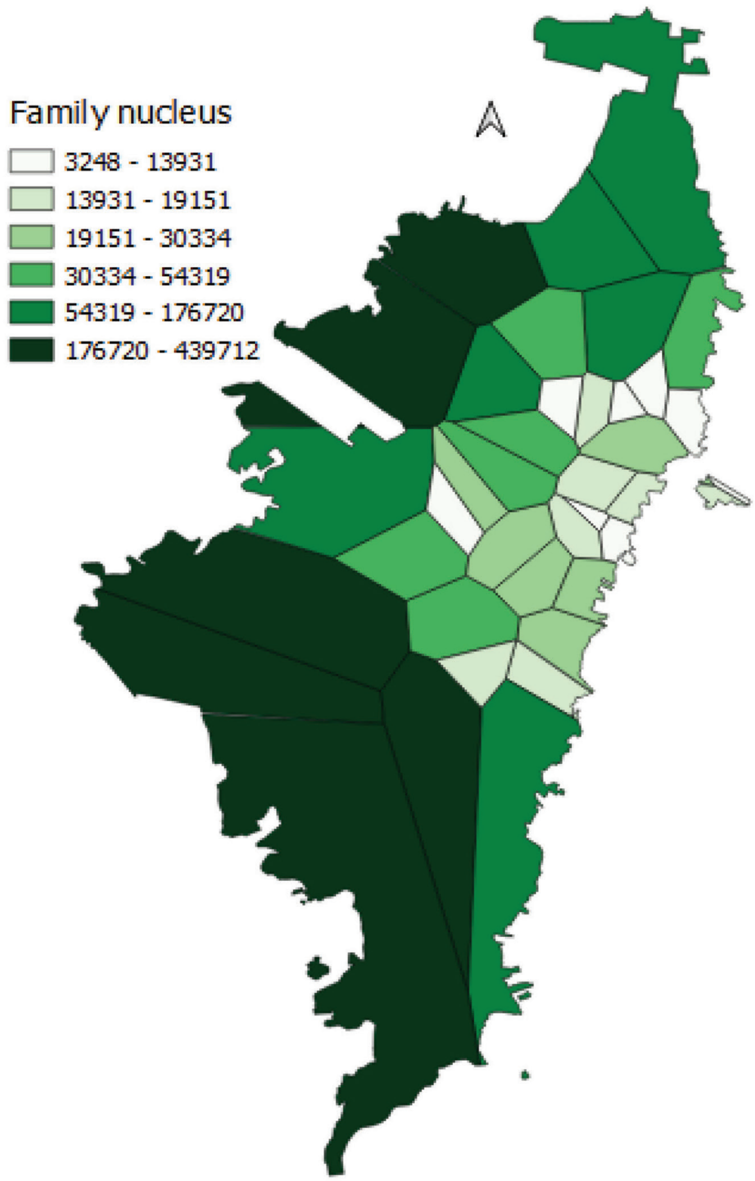
| Socioeconomic Levels | UPZs | Characteristics |
|---|---|---|
| 4, 5 and 6<br>(upper-middle and high) | ▪ some representatives<br>▪ UPZ Santa Bárbara<br>▪ UPZ Chicó Lago<br>▪ UPZ Usaquén<br>▪ UPZ Country Club<br>▪ UPZ La Alambra<br>▪ UPZ El Prado<br>▪ UPZ Los Andes<br>▪ UPZ El Refugio | ▪ High purchasing power<br>▪ Better access to housing and urban services<br>▪ Greater road infrastructure<br>▪ High quality of life |
| 1, 2, and 3 (low and lower-middle) | ▪ some representatives<br>▪ UPZ Lucero<br>▪ UPZ Arborizadora<br>▪ UPZ Tunjuelito<br>▪ UPZ Usme-Entrenubes<br>▪ UPZ Rafael Uribe Uribe | ▪ Less developed urban infrastructure<br>▪ Inferior road systems |

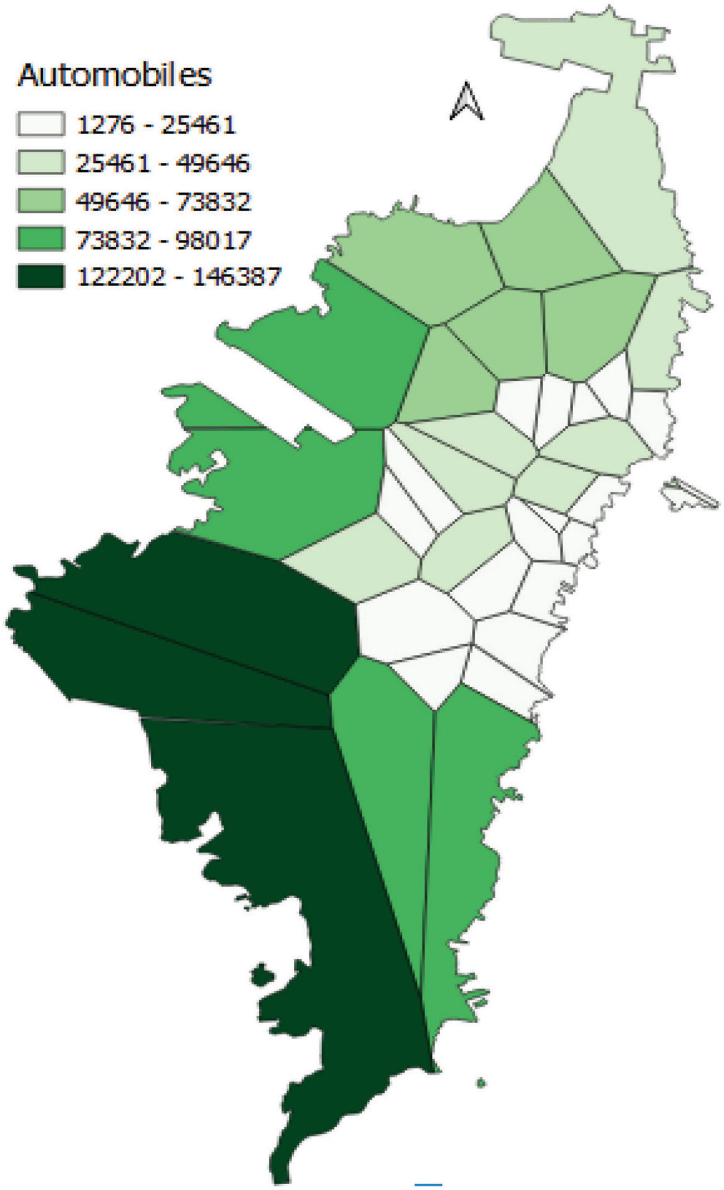
**Source:** Own elaboration.

A positive correlation can be observed between the number of automobiles and the number of nuclear families in each Voronoi zone, as shown in Figure 6. The southern areas of Bogotá exhibit a higher concentration of both variables, while the central and northern regions show lower densities of nuclear families and automobiles.

In addition, the relationship among nuclear families, automobile ownership, and socioeconomic level is analyzed. It is evident that the most prominent socioeconomic strata—levels 5 and 6—tend to have a lower number of nuclear families relative to the number of automobiles, indicating a higher vehicle-to-household ratio. This pattern is consistent with greater economic capacity, and suggests enhanced mobility and access to private transportation.

**Figure 6.** Automobiles per Voronoi Zone and Nuclear Families per Voronoi Zone






**Source:** Own elaboration.

The distribution of automobiles per nuclear family is categorized by socioeconomic level. A significant degree of variability is observed within socioeconomic level 5, whereas levels 2 and 6 display a more concentrated and consistent distribution.

On average, nuclear families in socioeconomic levels 1, 2, and 3 own approximately one automobile per household, while families in levels 5 and 6 possess an average of 1.5 automobiles per household.

This pattern may be influenced by Bogotá's license plate restriction policies (*pico y placa*) in effect at the time of this study. These policies limited the circulation of internal combustion vehicles on alternating weekdays. As a response, many individuals in higher socioeconomic groups acquired a second vehicle to bypass these restrictions, thereby increasing the average number of automobiles per household in those strata.

Figure 7, illustrates the correlation between the number of nuclear families and the number of automobiles, classified by the socioeconomic level of each UPZ. As in the previous figure, a clear relationship is observed between nuclear families and automobile ownership in relation to socioeconomic status.

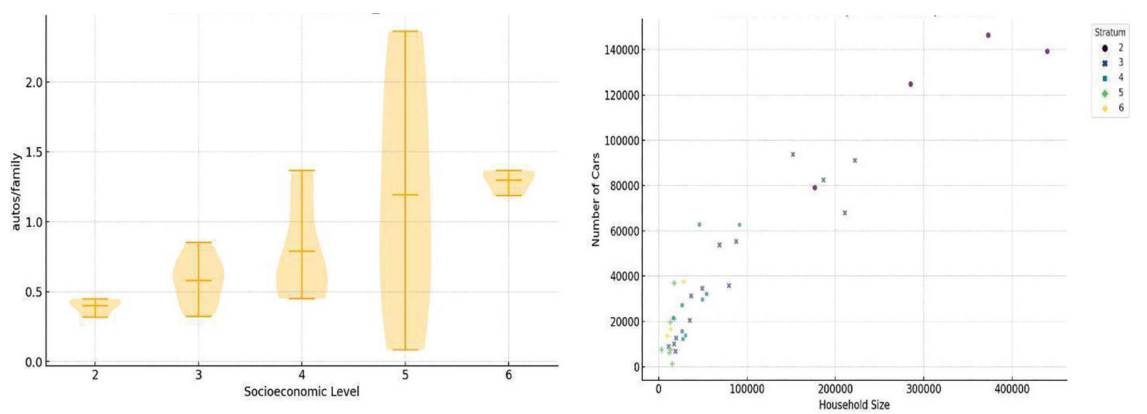
Socioeconomic level 2 records the highest number of nuclear families and, consequently, the greatest volume of automobiles, while levels 4, 5, and 6 display more stable and lower figures in both variables. This trend reflects the demographic structure of Bogotá D.C., where a large portion of the population belongs to lower and middle socioeconomic levels.

Figure 8, presents the number of points of interest (POIs) for EV charging infrastructure per 1,000 automobiles across different Voronoi zones in Bogotá, D.C. The zones are color-coded in shades of green, with darker areas—mostly in the city center and northern sectors—indicating a higher concentration of infrastructure, ranging from 7.14 to 50.16 POIs per 1,000 automobiles. In contrast, lighter-shaded regions, located primarily in southern and peripheral zones, show a lower density, with values between 1.11 and 2.54 POIs per 1,000 automobiles.

This spatial analysis highlights the uneven distribution of EV charging infrastructure in the city, pointing to significant disparities in accessibility. While the central areas benefit from dense networks of services and chargers, the peripheries remain underserved, emphasizing the need for more equitable and strategic urban planning to support the wider adoption of electric vehicles throughout all sectors of the city.

Numerous socioeconomic factors—including the distribution of nuclear families, existing infrastructure, and urban mobility dynamics—play a pivotal role in determining optimal locations for EV charging stations. Therefore, policy design for EV infrastructure in Bogotá, Colombia, must integrate both governmental planning and economic considerations to ensure efficiency, accessibility, and equity in the expansion of this essential service.

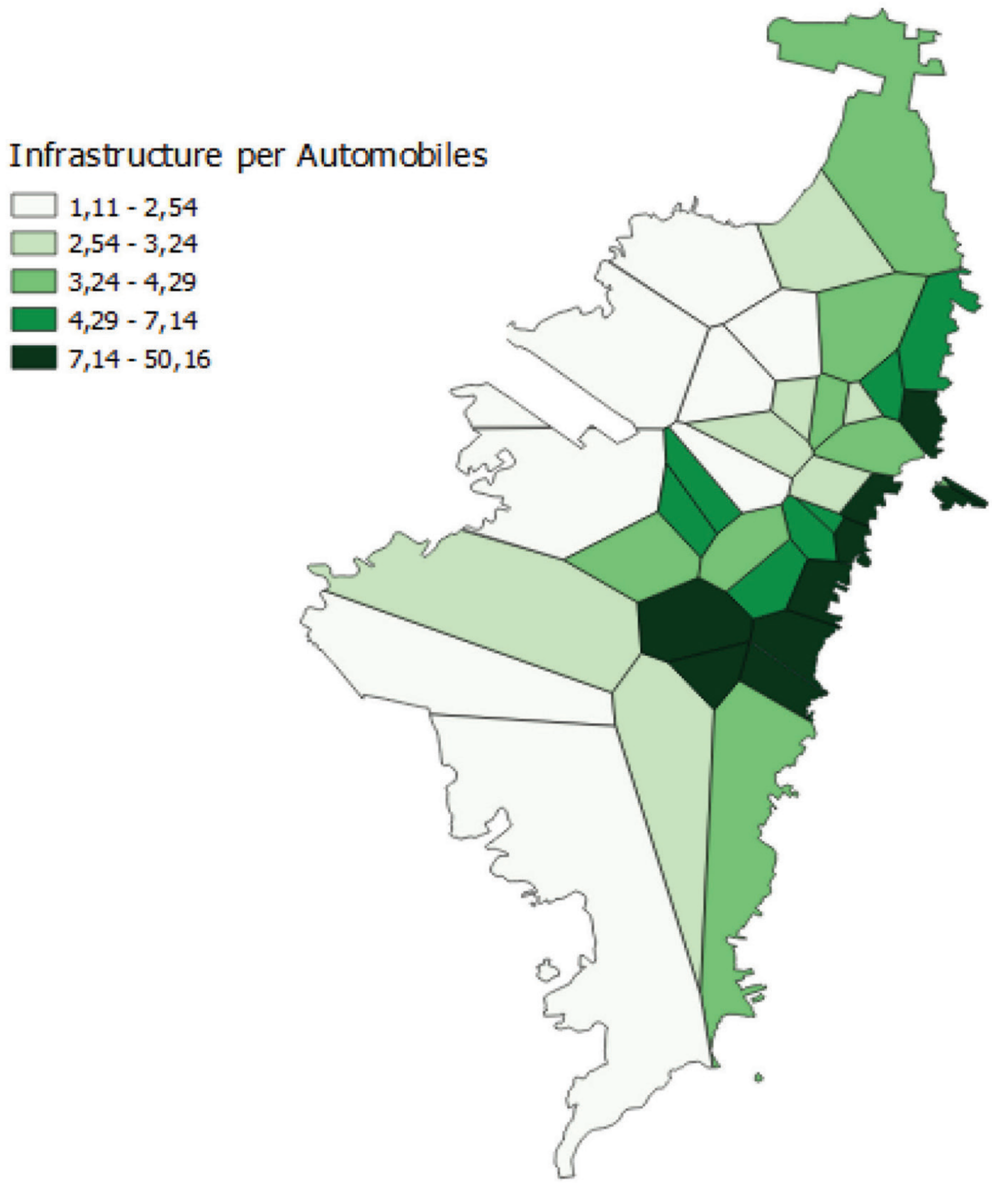
**Figure 7.** (a) Violin plot showing the distribution of automobiles per nuclear family across socioeconomic levels. (b) Relationship between nuclear families, automobiles, and socioeconomic level




(a) (b)

**Source:** Own elaboration.

**Figure 8.** Number of points of interest for charging station infrastructure per 1000 automobiles




**Source:** Own elaboration.

Areas with higher socioeconomic levels—specifically strata 5 and 6—exhibit a higher density of charging stations. These zones benefit not only from greater economic capacity, which facilitates the acquisition of electric vehicles (EVs), but also from superior infrastructure and access roads. In contrast, areas with lower socioeconomic levels (strata 1, 2, and 3) show a lower concentration of charging stations, reflecting reduced EV adoption due to economic limitations and less developed infrastructure.

The Voronoi region analysis conducted in this study effectively identifies the geographic zones closest to each charging station, thereby optimizing coverage and accessibility. Smaller Voronoi regions—mainly in the central and northern sectors of the city—correspond to a greater density of charging infrastructure, while the larger regions found in southern and peripheral areas reflect limited access to these services. This unequal distribution underscores the need for more equitable planning to promote the broader adoption of EVs across the entire urban territory.

The relationship between the number of automobiles per household and socioeconomic level demonstrates that the higher strata not only own more vehicles but also enjoy greater economic stability and better mobility conditions. These factors make high-income areas ideal for the initial deployment of charging stations, ensuring that the infrastructure is utilized efficiently and meets immediate demand.

To further reduce operating costs and improve sustainability, planning efforts should consider integrating renewable energy sources into charging station infrastructure. This strategy would allow for strategic positioning that maximizes clean energy use and helps mitigate overload on the electrical grid [36].

Overall, the findings reveal a non-uniform distribution of EV charging stations in Bogotá. However, they also highlight the potential for applying advanced geospatial tools in urban planning. The methodology based on Voronoi diagrams used in this study can be extended to other domains—such as the planning of essential services, green spaces, and public transportation systems. By doing so, urban planners can address spatial inequalities and make more efficient use of urban space, contributing to fairer and more sustainable urban development, even in cities with diverse socioeconomic contexts.

## Conclusion

There is significant variation in socioeconomic status both between and within geographic areas in urban environments. A positive correlation can be observed between Zonal Planning Units (UPZs) with higher income levels and greater access to services and infrastructure, which facilitates the ownership of private vehicles. In these UPZs, nuclear families not only enjoy higher economic capacity but may also experience limitations in the quality and availability of public transportation, making electric vehicles (EVs) a more attractive and viable alternative.

Moreover, UPZs with higher socioeconomic levels tend to be more meticulously planned and feature superior infrastructure, which plays a crucial role in facilitating private vehicle use. In contrast, UPZs with lower socioeconomic levels face significant challenges related to inadequate infrastructure, poorly maintained and unplanned roads, and limited parking availability, all of which pose obstacles to automobile ownership, particularly for EVs that require dedicated charging infrastructure.

The availability and efficiency of public transportation have been shown to be key determinants of the need for private vehicle ownership. In UPZs where public transportation is efficient, safe, and accessible, the necessity to own a car tends to decrease. In Bogotá, central UPZs classified as middle-income (level 3), where public transport coverage is relatively strong, exemplify this dynamic [37], [38].

Proposed solutions include the strategic deployment of EV charging stations in areas of high vehicular flow and in residential zones corresponding to socioeconomic levels 4, 5, and 6, ensuring an effective transition to electric mobility. However, urban planning policies must also emphasize equity in the distribution of charging infrastructure, aiming to promote adoption across all socioeconomic strata, not just in high-income areas.

Additionally, the integration of renewable energy sources—such as solar and wind power—into EV infrastructure development can optimize clean energy usage and minimize pressure on the existing power grid. This approach supports both environmental sustainability and long-term cost reduction, thereby encouraging wider and more equitable EV adoption in large urban centers.

Expanding the deployment of charging infrastructure into lower-income UPZs, especially when combined with upgrades to parking and roadway conditions, could encourage EV adoption in these areas. Such strategies should be accompanied by awareness campaigns that highlight the environmental and economic benefits of EVs, as well as incentives for the establishment of charging stations in strategic locations or points of interest.

By coordinating charging infrastructure expansion with renewable energy availability, cities can increase green energy usage while reducing the burden on the electrical grid. This dual approach enhances environmental performance, reduces operational costs, and further incentivizes the transition to electric vehicles in major cities [39], [40].

This study confirms that the current distribution of charging stations in Bogotá is influenced primarily by socioeconomic and infrastructural factors, with a higher concentration in wealthier areas and limited coverage in less affluent sectors. The application of Voronoi diagrams enabled the identification of underserved areas with limited access to EV infrastructure, emphasizing the need for equitable expansion policies. These findings underscore the importance of spatial analysis tools and data-driven planning models in optimizing EV infrastructure deployment, facilitating a more inclusive and sustainable transition to electric mobility in urban environments.

## References


[1] A. Brown, A. Cappellucci, E. White, A. Heinrich y E. Cost, *Electric Vehicle Charging Infrastructure Trends from the Alternative Fueling Station Locator: Second Quarter 2023*, National Renewable Energy Laboratory, NREL/TP-5400-87033, 2023, DOI:10.2172/2203059. National Renewable Energy Laboratory

[2] Molina et al., "Application of geostatistical techniques and their integration with tools such as geographic information systems (GIS)," 2021.

[3] Guzman et al., "The optimal location of EV charging stations is a pivotal factor in facilitating their adoption," 2023.

[4] M. S. Hossain *et al.*, "A Comprehensive Review on the Integration of Electric Vehicles for Sustainable Development," *Journal of Advanced Transportation*, vol. 2022, 11 Oct. 2022. DOI: 10.1155/2022/3868388.

[5] K. P. C. D. Cruz y L. K. S. Tolentino, "Unlocking the market potential of electric vehicles in the Philippines: A statistical and neural network approach to customer willingness to purchase electric vehicles," *International Journal of Innovative Research and Scientific Studies*, vol. 6, no. 4, pp. 888–902, 2023. [En línea]. Disponible: https://www.ijirss.com/index.php/ijirss/article/download/2088/397/3379

[6] Omahne *et al.*, "Social aspects of electric vehicles research—trends and relations to sustainable development goals," *World Electric Vehicle Journal*, vol. 12, no. 1, p. 15, 2021, DOI:10.3390/wevj12010015.

[7] Bernal-Vargas *et al.*, "Prospective analysis of massive integration of electric vehicle chargers and their impact on power quality in distribution networks," *World Electric Vehicle Journal*, vol. 14, no. 12, p. 324, 2023, DOI:10.3390/wevj14120324.

[8] Mojumder *et al.*, "Electric vehicle-to-grid (V2G) technologies: Impact on the power grid and battery," *Sustainability*, vol. 14, no. 21, p. 13856, 2022, DOI:10.3390/su142113856.

[9] A. Rabie, A. Ghanem, S. S. Kaddah y M. M. El-Saadawi, "Enhancing the performance of radial distribution systems via optimal integration of electric vehicles," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 4, pp. 2514–2526, diciembre 2023, DOI:10.11591/ijpeds.v14.i4.pp2514-2526.

[10] Y. Zhang, Y. Wang, F. Li, B. Wu, Y.-Y. Chiang y X. Zhang, "Efficient deployment of electric vehicle charging infrastructure: Simultaneous optimization of charging station placement and charging pile assignment," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 11, pp. 6654–6659, 2021. [Online]. DOI: https://doi.org/10.1109/TITS.2020.2990694.

[11] B. Javed, M. Kandlikar y A. Giang, "Variability in costs of electrifying passenger cars in Canada," *Environmental Research: Infrastructure and Sustainability*, vol. 4, no. 1, Art. 015008, 2024.

[12] Unterluggauer *et al.*, "Electric vehicle charging infrastructure planning for integrated transportation and power distribution networks: A review," *eTransportation*, vol. 12, p. 100163, 2022, DOI:10.1016/j.etran.2022.100163.

[13] Sadeghian *et al.*, "A comprehensive review on electric vehicles smart charging: Solutions, strategies, technologies, and challenges," *Journal of Energy Storage*, vol. 54, p. 105241, 2022, DOI:10.1016/j.est.2022.105241.

[14] S. Erdoğan, İ. Çapar, İ. Çapar y M. M. Nejad, "Establishing a statewide electric vehicle charging station network in Maryland: A corridor-based station location problem," *Socio-Economic Planning Sciences*, vol. 79, p. 101127, 2022.

[15] S. Alkhalisi, "Creating a qualitative typology of electric vehicle driving: EV journey-making mapped in a chronological framework," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 69, pp. 159–186, 2020, DOI:10.1016/j.trf.2020.01.009.

[16] Feng *et al.*, "Review of electric vehicle charging demand forecasting based on multi-source data," in *2020 IEEE Sustainable Power and Energy Conference (iSPEC)*, pp. 139–146, 2020. [Online]. Disponible: DOI https://doi.org/10.1109/iSPEC50848.2020.9351008.

[17] Janjić *et al.*, "Estimating the optimal number and locations of electric vehicle charging stations: The application of multi-criteria p-median methodology," *Transportation Planning and Technology*, vol. 44, no. 8, pp. 827–842, 2021, DOI:10.1080/03081060.2021.1992177.

[18] A. Llopis Herrero, *Desarrollo de un simulador de carga de vehículos eléctricos a nivel interurbano*, Tesis doctoral, Universitat Politècnica de València, 2023. [En línea]. Disponible: http://hdl.handle.net/10251/192785

[19] Arias *et al.*, *Estadística espacial: Fundamentos y aplicación con sistemas de información geográfica*. Ciudad Autónoma de Buenos Aires: Impresiones Buenos Aires, 2021.

[20] G. Buzai, "Áreas de influencia de los centros de atención primaria de salud (CAPS) en la ciudad de Luján mediante polígonos de Voronoi-Thiessen," Instituto de Investigaciones Geográficas, 2016. [En línea]. Disponible: http://hdl.handle.net/11336/118055

[21] N. C. Principi, *Análisis de la estructura socioespacial regional: Aplicación de Sistemas de Información Geográfica (SIG) al noroeste de la Provincia de Buenos Aires (Argentina)*. Editorial Académica Española, 2013.

[22] Departamento Administrativo Nacional de Estadística (DANE), "Estratificación socioeconómica urbana para servicios públicos domiciliarios," 2015. [En línea]. Disponible: https://www.dane.gov.co/files/geoestadistica/estratificacion/ManualdeRealizacion.pdf

[23] ENEL, *Puntos de recarga de vehículos eléctricos*, Enel Colombia SA ESP, 2022.

[24] Electromaps, "Puntos de carga en Bogotá – base de datos (7 estaciones en Bogotá; punto más reciente: WorkMates Masterline, añadido el 18 12 2024)," *Electromaps*, 2025. [En línea]. Disponible: https://www.electromaps.com/es/puntos-carga/colombia/bogota

[25] Enel X, "Nueva estación de carga en Centro Comercial Unicentro Bogotá (4 espacios; 60 kW, 30 kW y 30 kW)," *Enel X*, mar. 2025. [En línea]. Disponible: https://www.enelx.com/co/es/historias/nueva-estacion-de-carga-unicentro

[26] Terpel Voltex, "Infraestructura de recarga para movilidad eléctrica – Corporativo Bogotá (Carrera 7 No. 75 51)," *Terpel*, 2025. [En línea]. Disponible: https://www.terpel.com/nueva-movilidad-y-energias/terpel-voltex

[27] Dielco, "Mapa de electrolineras Dielco – estaciones de recarga en Bogotá," *Electrolineras Dielco*, 2025. [En línea]. Disponible: https://electrolineras.dielco.co/

[28] J. A. Piraquive Rodríguez y D. E. Dimaté Mora, "La eficacia de los presupuestos participativos en la localidad de Sumapaz a nivel local," 2024.

[29] DANE, "Geoportal," 2024. [En línea]. Disponible: https://geoportal.dane.gov.co/#gsc.tab=0

[30] Alcaldía Mayor de Bogotá, *Bogotá mi ciudad*, 2024a.

[31] Alcaldía Mayor de Bogotá, *Datos abiertos Bogotá*, 2024b.

[32] OpenStreetMap contributors, "OpenStreetMap: The free wiki world map," 2024. [En línea]. Disponible: https://www.openstreetmap.org

[33] DANE, "Boletín Técnico ECV 2021," 2024. [En línea]. Disponible: https://www.dane.gov.co/files/investigaciones/condiciones_vida/calidad_vida/2021/Boletin_Tecnico_ECV_2021.pdf

[34] Free Software Foundation, "GNU General Public License, Version 3," 2007. [En línea]. Disponible: https://www.gnu.org/licenses/gpl-3.0.html

[35] G. D. Buzai y E. J. Montes Galván, *Estadística espacial: Fundamentos y aplicación con sistemas de información geográfica*. Universidad Nacional de Luján, Instituto de Investigaciones Geográficas, 2021.

[36] S. Li, O. Gao y F. You, "AI for Science in Electrochemical Energy Storage: A Multi-Scale Systems Perspective on Transportation Electrification," *Nexus*, 2024.

[37] D. Toro González, V. M. Cantillo Maza y A. Espinosa Espinosa, "La demanda de transporte público en Colombia, 2000-2010," 2018.

[38] E. Guerra, "The built environment and car use in Mexico City: Is the relationship changing over time," *Journal of Planning Education and Research*, vol. 34, no. 4, pp. 394–408, 2014.

[39] H. R. Sayarshad, "Optimization of electric charging infrastructure: integrated model for routing and charging coordination with power-aware operations," *npj Sustainable Mobility and Transport*, vol. 1, no. 1, Art. 4, 2024.

[40] F. Hao, "Impact of electric vehicle charging demand on clean energy regional power grid control," *Energy Informatics*, vol. 8, no. 1, p. 1, 2025.