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Spatial Inequality in Electric Vehicle Charging Infrastructure*

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Abstract:

Purpose: *The growing development of electromobility has increased the importance of charging infrastructure as a key component of low-emission urban transport systems. However, the number of charging stations alone does not provide a sufficient measure of infrastructure accessibility, as their spatial distribution and the number of charging points available at each station also determine network coverage. This study aims to assess the spatial unevenness of electric vehicle charging infrastructure and propose a procedure for identifying its spatial concentration and shortage areas, using Warsaw, Poland, as a case study.*

Design/methodology/approach: *The analysis draws on data concerning electric vehicle charging stations and charging points, combined with Warsaw's administrative boundaries. Following data processing and spatial filtering, the final dataset comprised 909 charging points distributed across 501 stations. The analytical procedure involved point mapping, two-dimensional kernel density estimation, spatial analysis using regular square and hexagonal grids at a resolution of 1 km, identification of infrastructure shortage areas, and calculation of a synthetic spatial concentration index. This integrated approach enabled the assessment of local density patterns, spatial gaps and the concentration of charging infrastructure across the city.*

Findings: *The results indicate that, although Warsaw has a relatively extensive charging network in numerical terms, its spatial distribution is markedly uneven. Charging-point density is highest in the central and central-western parts of the city, whereas peripheral areas are comparatively poorly served. The concentration index reaches 75.69%, indicating that the 10% most saturated hexagonal grid cells contain more than three-quarters of all charging points. Furthermore, the network is characterised by a predominantly small-scale facility structure, with most stations comprising only one or two charging points.*

Practical implications: *The proposed procedure can support urban transport and infrastructure planning by identifying areas of high charging-point concentration, locations with insufficient provision and parts of the city where infrastructure expansion may be required. Combining point mapping, density estimation, grid-based analysis and a*

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concentration index provides a transparent and replicable framework for assessing the spatial unevenness of urban electric vehicle charging infrastructure.
Originality/value: *The study contributes a spatially integrated procedure for evaluating urban charging infrastructure that goes beyond station counts by accounting for the distribution of individual charging points. Its application to Warsaw demonstrates how complementary spatial analytical techniques can reveal local concentration patterns and infrastructure gaps, thereby providing an evidence-based foundation for planning more spatially balanced charging networks.*

Keywords: *Electromobility, Electric vehicle charging infrastructure, Spatial analysis, Urban accessibility, Kernel density estimation, Transport planning.*

JEL Classification: *R41, R58, O18.*

Article type: *Research article.*

1. Introduction

The development of electromobility is one of the key elements of the changes taking place in urban transport, particularly in the context of reducing emissions, improving the accessibility of transport services and implementing solutions that fit within the concept of a low-carbon economy. However, the widespread practical adoption of electric vehicles depends not only on an increase in their numbers, but also on the development of the infrastructure enabling their daily use.

The literature emphasises that access to charging remains one of the factors influencing the rate of adoption of electric vehicles, and the importance of public infrastructure is increasing particularly where users are unable to charge their vehicles at home or at work (Hardman *et al.,* 2018; Funke *et al.,* 2019; IEA, 2025). At the European level, this issue has been further reinforced by regulations on the development of alternative fuel infrastructure, which highlight the need to create an accessible, interoperable and user-friendly network (European Parliament and Council, 2023; Gładysz *et al.,* 2026).

In this context, the assessment of the charging network should not be limited solely to determining the number of stations operating within the city limits. It is equally important to identify in which parts of the urban space this infrastructure is concentrated, where shortages exist, and whether the existing distribution of charging points promotes equitable accessibility.

Existing research indicates that the electric vehicle charging network may exhibit marked spatial variation, and its concentration in selected locations may lead to the perpetuation of underserved areas (Roy and Law, 2022; Wang *et al.,* 2024; Gazmeh

et al., 2024). This issue is of particular significance in large urban centres, where infrastructure development depends on demand, the attractiveness of the location, operators' decisions and the city's functional structure.

The aim of this study is to assess the spatial distribution and degree of concentration of electric vehicle charging points in Warsaw. The analysis seeks to identify areas with high infrastructure density, underserved areas, and potential infrastructure deficits within the urban space. The study utilised a GIS approach, encompassing point mapping, density estimation, data aggregation in regular spatial grids, and the classification of units according to the level of infrastructure accessibility.

In the case of charging infrastructure, the level of analytical detail is particularly important. Data on such facilities usually have a hierarchical structure, as they refer to both stations and charging points. A station constitutes a locational and registration unit, whereas a charging point is functional in nature, as it directly determines the ability to charge a vehicle.

This means that a single station may comprise one or several points, and thus an approach based solely on stations may oversimplify the assessment of the network's actual capacity and spatial availability. For this reason, this study adopts the charging point as the basic unit of analysis, whilst retaining information on stations in order to capture the organisational structure of the infrastructure.

The novelty of the study lies in the application of a detailed, point-based approach to EV infrastructure at an intra-urban scale, rather than limiting the analysis to the number of stations or aggregated administrative data. This approach makes it possible to capture not only the location of facilities, but also their actual functional capacity resulting from the number of available charging points. An additional strength of the study is the combination of several spatial analysis methods, including point mapping, density estimation, and aggregation in square and hexagonal grids, which enables the identification of both areas of concentration and infrastructure deficits within the boundaries of Warsaw.

Although the empirical analysis concerns Warsaw as the largest city in Poland, the proposed research procedure is transferable and can be adapted to other cities and metropolitan areas. It requires only the availability of data on the location of stations and charging points, as well as the boundaries of the analysed area. As a result, it can serve as a replicable framework for assessing the spatial accessibility of EV infrastructure in various urban contexts.

2. Literature Review

The development of electric vehicle charging infrastructure is treated in the literature as one of the fundamental conditions for the widespread adoption of electromobility. Research indicates that users' decisions regarding the purchase and operation of

electric vehicles depend not only on the technical parameters of the vehicles, but also on the availability and convenience of the charging infrastructure *(Hardman et al.,* 2018). The importance of the public charging network is growing, particularly in areas where users are unable to charge their vehicles regularly at home or at work (Funke *et al.,* 2019).

For this reason, the planning of charging infrastructure is considered in the context of both user behaviour and the organisation of urban transport, as well as the city's spatial structure. Location studies emphasise that the placement of stations should take into account demand, availability of space, and links to users' daily journeys (Lam *et al.,* 2014). A similar approach is found in optimisation analyses, in which the location of charging infrastructure is treated as an element supporting the functioning of the urban transport system (Sadeghi-Barzani *et al.,* 2014).

A significant area of research involves analyses of the spatial variation and uneven availability of public charging infrastructure. The mere presence of stations within a city or region does not in itself imply an even distribution of facilities or comparable accessibility for users. Roy and Law (2022) point out that the distribution of charging stations can reveal clear spatial disparities that are not apparent when analysing solely the number of facilities.

In turn, Wang *et al.* (2024) demonstrate that the assessment of charging infrastructure requires a multidimensional approach, encompassing not only location but also the intensity and structure of distribution. The literature also notes that charging infrastructure may be concentrated in central, commercial or better-connected areas, whilst peripheral areas remain relatively underserved (Carlton and Sultana, 2023). For this reason, measures of spatial accessibility, neighbourhood analyses and concentration indices are increasingly being used, as they allow us to identify not only the number of facilities but also their distribution in relation to the urban structure (Gazmeh *et al.,* 2024).

GIS methods, point-based analyses, density estimation and grid-based approaches are widely used in studies on the distribution of charging infrastructure. Kernel density estimation allows one to move from a set of points to a continuous intensity surface, thereby facilitating the identification of local concentration zones (Silverman, 1986). This method is frequently used in point analyses as it enables a synthetic representation of the spatial intensity of the phenomenon under study without the need to be restricted to administrative boundaries (Gatrell *et al.,* 1996).

In turn, analyses conducted on regular grids allow for the comparison of infrastructure density in units of similar area; however, their results may depend on the chosen method of spatial aggregation (Openshaw, 1984). This problem is known in spatial analysis as the modifiable areal unit problem (MAUP), which can influence the interpretation of results. In this context, hexagonal grids are a useful

tool for organising data, as they provide more uniform neighbourhood relationships than conventional square grids (Uber Technologies, 2018).

These findings therefore justify the use of a procedure combining point mapping, density estimation, grid analysis and a concentration index. This approach remains consistent with the objective of this study, which is to identify the spatial unevenness of electric vehicle charging infrastructure in Warsaw from the perspective of charging points, rather than solely charging stations.

3. Methodology

3.1 Analysis of Point Distribution

The first stage of the analysis involved visualising the distribution of all charging points within the administrative boundary of Warsaw. In this context, the point map serves primarily as a diagnostic and exploratory function, as it enables a preliminary assessment of the overall spatial layout of the infrastructure (Gatrell *et al.,* 1996). It makes it possible to determine whether charging points tend to be scattered, evenly distributed, or concentrated in specific parts of the city. At the same time, it enables the identification of potential axes of network development and areas where the infrastructure appears particularly dense or relatively underdeveloped.

Although the point map does not yet provide synthetic measures, it constitutes an important stage in the analysis of empirical data, allowing the basic characteristics of the distribution of facilities to be captured and preliminary spatial patterns to be identified. n practice, it also enables an assessment of whether the observed pattern of points suggests the presence of clusters, peripheral areas of scarcity, or linear concentrations of infrastructure associated with major transport corridors and areas of high urban functional intensity. For this reason, point visualisation served as the starting point for further stages of the analysis, in which more formalised methods of identifying spatial concentration and variation were applied.

3.2 Density Estimation

To identify zones with a higher density of charging point locations, two-dimensional kernel density estimation (KDE) was used (Silverman, 1986; Gatrell *et al.,* 1996). This method enables the transition from a discrete set of points to a continuous intensity surface thereby allowing for a more effective representation of the spatial structure of infrastructure distribution and the identification of concentration areas that are not always clearly visible on a point map (Okabe *et al.,* 2009).

The advantage of this approach is the ability to reveal local centres of point accumulation, regardless of the arbitrary division of space into administrative units or grid cells. The general form of the density estimator is as follows:

$$\hat{f}(s) = \frac{1}{nh^2} \sum_{i=1}^{n} K\left(\frac{\| s - s_i \|}{h}\right) \quad (1)$$

Where n is the number of charging points, h is the smoothing parameter, or bandwidth, $K(\cdot)$ is the kernel function, s is the location at which the density value is estimated, and s_i is the location of the i-th charging point. In practice, this procedure assigns an influence function to each point, with the influence decreasing as distance increases, and then sums the influence of all points within the analysed space. The result is a continuous surface representing the relative intensity of the phenomenon under study.

The result of the estimation should not be interpreted as an exact number of points per unit area, but rather as a measure of the relative intensity of the distribution, allowing different parts of the study area to be compared in terms of infrastructure concentration. The use of KDE therefore enables the identification of main concentration nuclei, transition zones and areas with low infrastructure density. In this study, the density estimation complemented the point map analysis and served as a tool for a more comprehensive spatial assessment of the layout of charging points.

3.3 Analysis in a Regular Grid

In the next stage, two analytical grids with a 1 km mesh size were used, namely a square and a hexagonal grid. The square grid is well suited to simple counting and comparisons, whereas the hexagonal grid reduces the effect of directionality and is often preferred in spatial analyses when the aim is to identify local centres of concentration (Birch *et al.,* 2007).

The use of regular grids allows the intensity of a phenomenon to be compared across units of similar area, although it must be borne in mind that the results of the analyses may depend on the method of spatial data aggregation adopted (Openshaw, 1984; Wong, 2004). For each cell i, the number of charging points n_i, the number of stations s_i , the point density d_i and the average number of connectors per point $\bar{c}_i$ were calculated. Point density was determined using the formula:

$$d_i = \frac{n_i}{A_i} \quad (2)$$

The average number of connectors per point in a cell was calculated as:

$$\bar{c}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} c_{ij} \quad (3)$$

In Equations (2)–(3), n_i is the number of charging points and s_i is the number of stations in grid cell i, while A_i represents the area of that cell. Accordingly, d_i expresses the density of charging points per unit area.

The term c_{ij} refers to the number of connectors available at charging point j in cell i, and $\bar{c}_i$ is the mean number of connectors per charging point within that cell. Thus, d_i captures the spatial concentration of charging infrastructure, whereas $\bar{c}_i$ provides a complementary measure of local connector availability.

When applying Equation (3), $\bar{c}_i$ is calculated only for cells with $n_i > 0$. For cells without charging points, the mean number of connectors is not defined.

3.4 Identification of Areas with Insufficient Infrastructure

The identification of areas with infrastructure shortages was carried out using a hexagonal grid, applying a threshold rule based on the distribution of charging point density. The choice of this grid was due to its advantageous properties in spatial analyses, particularly the reduction of directionality effects and the attainment of more homogeneous neighbourhood relations between units (Birch *et al.,* 2007). Deficit areas were understood as parts of the urban space that were less well-equipped relative to the overall distribution of infrastructure in Warsaw.

Two categories of spatial units were identified as deficit cells. The first consisted of cells completely devoid of charging points, meaning an absolute lack of the infrastructure under analysis. The second category comprised cells with low accessibility, defined as a density of charging points not exceeding the first quartile of the distribution of positive density values. The formal classification rule is as follows:

$$D_i = \begin{cases} 1, & \text{if } n_i = 0 \text{ or } (n_i > 0 \text{ and } d_i \leq Q_1(d_i \mid d_i > 0)), \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

In Equation (4), D_i is a binary variable indicating whether grid cell i is classified as deficient or non-deficient. The variable n_i represents the number of charging points in cell i, while d_i expresses the density of charging points in that cell. The term $Q_1(d_i \mid d_i > 0)$ refers to the first quartile of the distribution of positive density values, calculated after excluding cells with zero charging point density (Tukey, 1977). The use of the first quartile follows a descriptive approach based on the relative position of each observation within the empirical distribution.

The indicator defined in this way is relative in nature, as it does not refer to a normatively established threshold for infrastructure provision, but rather identifies areas with the lowest accessibility within the spatial system under analysis. Adopting this approach reduces the arbitrariness of the classification and allows the

identification of deficits to be adapted to the internal structure of the area under study. Consequently, the method serves to identify parts of the city that may require further comparative or planning analysis.

3.5 Spatial Concentration Index

To provide a synthetic overview of the degree of spatial concentration of infrastructure, an index was calculated to determine the proportion of charging points located within the top 10% of hexagonal cells. This measure makes it possible to assess the extent to which infrastructure is concentrated in a limited number of locations and thus serves as a tool for describing the unevenness of its distribution across the city.

The construction of the index is based on the classical approach to measuring concentration, in which units are ordered according to the intensity of the phenomenon under study and the cumulative share falling within a selected part of the distribution is then analysed. The index is expressed as follows:

$$C_{10} = \frac{\sum_{i=1}^{\lceil 0.10N \rceil} n_{(i)}}{\sum_{i=1}^{N} n_{(i)}} \cdot 100 \qquad (5)$$

In Equation (5), C_{10} is the spatial concentration index, N is the total number of cells in the hexagonal grid, and $n_{(i)}$ is the number of charging points in the i-th cell after sorting all cells in descending order by infrastructure saturation. The numerator represents the number of charging points located in the top 10% of cells, while the denominator represents the total number of charging points in the analysed system.

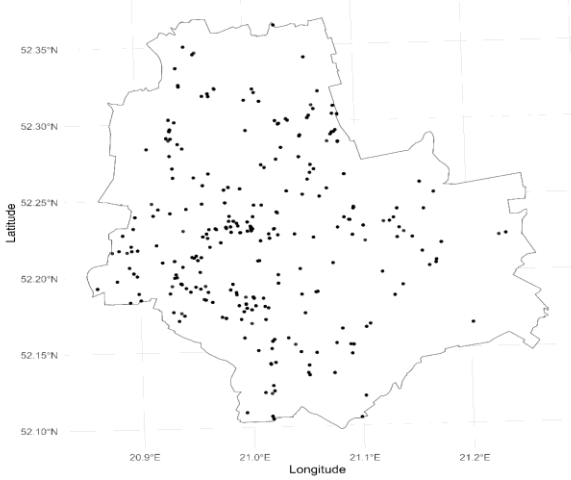
The interpretation of the indicator is intuitive. The higher its value, the greater the concentration of infrastructure in a small number of spatial units. A low value indicates a more even distribution of charging points. In this study, C_{10} serves as a complement to maps and grid analyses, as it reduces a complex spatial pattern to a single measure of the concentration of infrastructure.

4. Research Results and Discussion

4.1 Distribution of points within the city limits

The map of points indicates that EV infrastructure in Warsaw is not distributed evenly (Figure 1). The highest concentration of points occurs in the central zone and in the belt located to the west and south-west of the city centre. Individual secondary clusters are also visible in the northern and north-eastern parts. On the outskirts of the city, points are significantly less frequent and distributed in a more scattered manner.

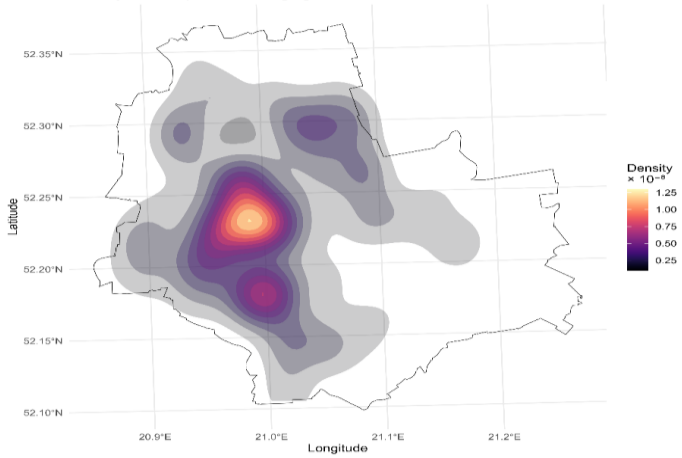
Figure 1. *Distribution of EV charging points in Warsaw.*



Source: *Authors' calculations.*

The KDE plot (Figure 2) confirms the existence of several distinct hotspots. The strongest concentration is in the central-western part of the city, with further areas of increased intensity occurring in the central-southern belt and in the northern part. This means that the network is developing not by evenly covering the entire city, but rather by increasing the density of selected locations.

Figure 2. *Area of EV charging point density in Warsaw (KDE).*



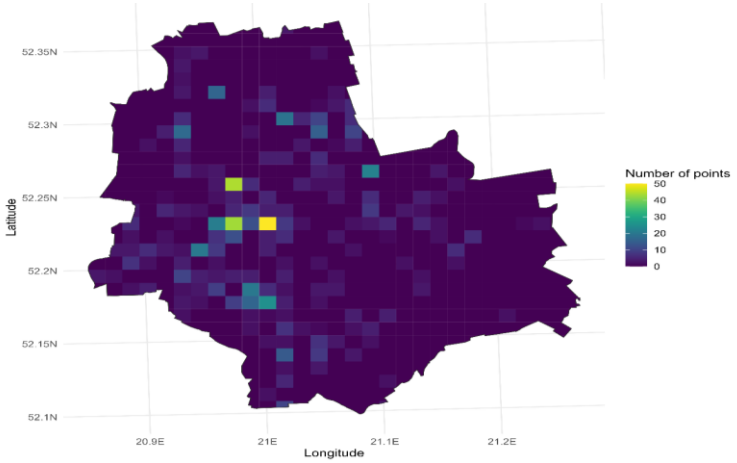
Source: Author's calculations.

4.2 Grid-Based Distribution and Spatial Concenrtation

The map in a 1 × 1 km square grid (Figure 3) shows that the highest numbers of points are found in a small number of cells located in the central part of Warsaw. The hexagonal grid confirms this pattern and, at the same time, better highlights the

spatial continuity of high-density zones. In practice, this means that the intensive development of the infrastructure is cluster-based.

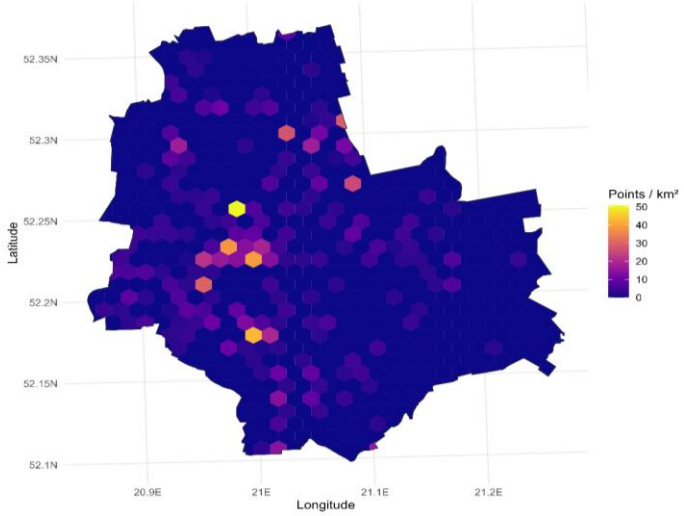
Figure 3. *Number of EV points in a 1 km × 1 km square grid.*



Source: *Authors' calculations.*

The concentration index C_{10} was 0.7569, meaning that the 10% most saturated hexagons contained 75.69% of all charging points. This is a very high figure, indicating significant spatial unevenness. In other words, the vast majority of the infrastructure is concentrated in a relatively small part of the city, whilst vast areas remain poorly served. This relationship is shown in Figure 4.

Figure 4. *Density of EV charging points in a hexagonal grid.*



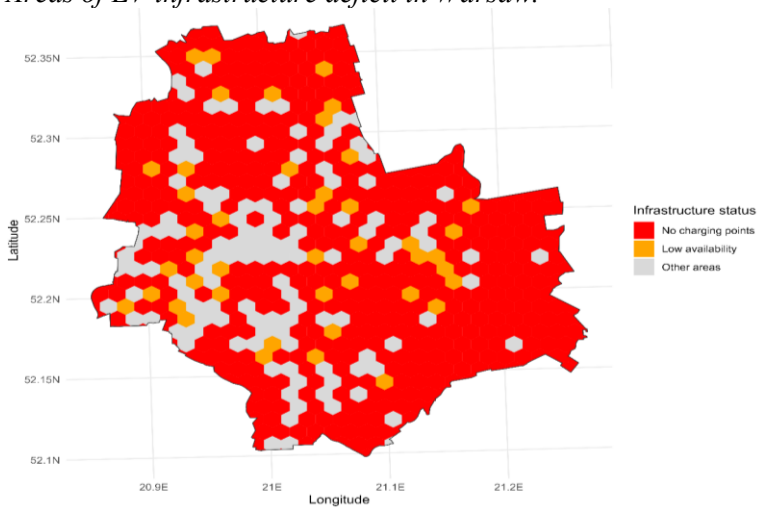
Source: *Authors' calculations.*

4.3 Areas with Infrastructure Shortages

The map of areas with a shortage (Figure 5) shows that cells without charging points are predominantly found on the city's outskirts, whilst areas classified as 'low availability' often form a transitional zone between the core of the concentration and the city's outer belt. This result is typical of demand-driven infrastructure development and stems from the fact that operators first strengthen locations with high visibility and significant usage potential, and only later expand the network to more dispersed areas.

This indicates that the observed shortage reflects a structural pattern rather than isolated gaps in coverage. It is not just a matter of individual vacant units, but of entire sections of urban space remaining outside the main infrastructure core. From an urban policy perspective, this implies a need to shift from a logic of strengthening existing hotspots to a logic of completing the network.

Figure 5. *Areas of EV infrastructure deficit in Warsaw.*



Source: *Authors' calculations.*

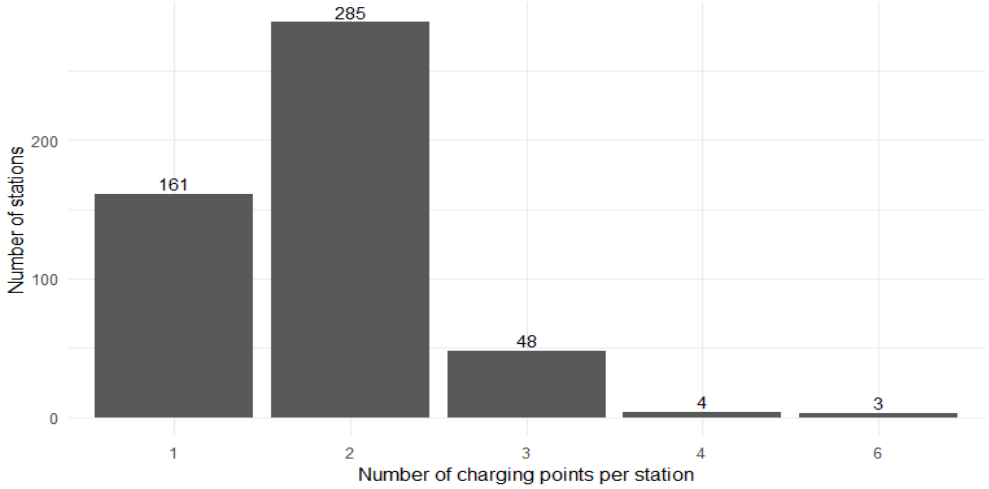
The 'other' category includes cells where charging infrastructure is present, and its density exceeds the low-availability threshold determined by the first quartile of the point density distribution.

4.4 Station Structure and Number of Points

A total of 501 EV charging stations were identified in Warsaw. After merging station and point data and eliminating records lacking information on connectors and charging solutions, the final analytical dataset comprised 909 EV charging points, assigned to 501 charging stations, corresponding to an average of 1.81 points per station. The median number of points per station is 2, and the maximum value is 6.

The distribution of the number of points per station is right-skewed, with a clear predominance of small stations, as shown in Figure 6. In total, 89.02% of stations have 1 or 2 charging points, whilst stations with at least three charging points account for only 10.98% of the analysed stations.

Figure 6. *Distribution of the number of points per station in Warsaw.*



Source: *Authors' calculations.*

This result suggests that the development of charging infrastructure in Warsaw has primarily involved increasing the number of small and medium-sized locations, rather than creating large, multi-point charging hubs. The network structure therefore points to a development model based on the spatial dispersion of relatively small facilities, which may help improve the overall accessibility of the infrastructure across the city, but does not necessarily imply high capacity at individual locations.

At the same time, the dataset is dominated by points equipped with a single connector, which further confirms the small-scale rather than high-capacity nature of a significant part of Warsaw's charging network. This means that in many cases the capacity to serve users at a single location remains limited, and the system's ability to absorb increased demand may be uneven both spatially and functionally.

4.5 Discussion and Limitations

The analysis shows that the spatial structure of EV infrastructure in Warsaw is strongly polycentric, yet uneven. There are several centres of concentration in the city, but they do not form a pattern that evenly covers the entire territory The core of the network is located mainly in the central and central-western parts of the city and their immediate surroundings. This pattern underscores the importance of spatial analyses, as the mere number of stations or charging points does not allow for an

assessment of whether the infrastructure is equally accessible across different parts of the city (Roy and Law, 2022; Wang *et al.,* 2024).

From the user's perspective, the mere presence of infrastructure in the city does not equate to equal spatial accessibility. For operators and local authorities, this signals that further investments should not be concentrated solely where the network is already dense, but also where spatial gaps exist that limit service continuity.

This is consistent with an approach in which the location of charging infrastructure should be assessed not only in terms of the number of facilities, but also their impact on the ability to serve journeys, spatial accessibility and integration with the urban layout (Sierpiński *et al.,* 2020; Schmidt *et al.,* 2021).

A limitation of the study is its spatial-descriptive nature. The analysis does not cover qualitative variations in infrastructure in terms of charging power, connector type, operating hours, reliability or the actual utilisation of charging points. Potential demand, such as population size, electric vehicle registrations, land use functions or traffic volume, has also not been taken into account.

This is significant because the development of the electric vehicle market should be analysed in conjunction with the dynamics of charging infrastructure development and the conditions for its practical use (Borucka *et al.,* 2024; Liniewski *et al.,* 2025). The shortage indicator used is therefore relative in nature and should be interpreted as a tool for intra-city comparisons, rather than an absolute standard of sufficiency. In further research, the procedure could be extended to include demand and socio-spatial data, as the availability of charging infrastructure is increasingly analysed from the perspective of spatial justice and equitable access to transport services (Carlton and Sultana, 2023).

5. Conclusions

Warsaw's electric vehicle charging infrastructure is numerically well-developed but unevenly distributed. Point analysis, density estimation and regular grids all lead to the same conclusion: the network has a strong core of concentration in the central part of the city, whilst numerous peripheral areas remain poorly served. The high value of the C_{10} (75.69%) confirms that the infrastructure is concentrated in a small number of spatial cells.

At the same time, the structure of the stations indicates a predominance of small facilities with 1–2 points, meaning that the system's development is taking place through scattered locations of limited scale rather than through the dominance of large hubs. From a practical perspective, this means that further network expansion should combine two objectives: closing spatial gaps on the city's outskirts and strengthening capacity in areas already under intensive use.

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