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Spatial Data Gap Analysis of Electric Vehicle Charging Points*

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Abstract

Despite the considerable advancement of various technologies based on broadly defined digitalization, the phenomenon of electromobility is still a niche area, especially in terms of implementing new charging points in the human sphere. Undoubtedly, this is an area of human activity where very important decisions are made regarding taking action to reduce exhaust emissions, so crucial for future generations. Therefore, the phenomenon of electromobility, related to aspects of transport tasks, is linked to all issues related to the movement of people and cargo using electric vehicles (EVs), which in turn depends on the location of charging points, which are part of the alternative fuel infrastructure.

Given the importance of this evolving phenomenon, it is crucial to demonstrate the potential for developing infrastructure for electric vehicles, but also to define areas where this development is hindered for various reasons. This led to an investigation into the existence of data gaps in the area of electromobility, with particular emphasis on the allocation of charging points within the context of human activity. The direction of the research was also determined by the existing literature gap in the analyzed research area.

The aim of this article was to interpolate the gaps in spatial data for electric vehicle charging points across the Republic of Poland. In this article, to demonstrate the gaps in spatial data, i.e., electric vehicle charging points, it was deemed appropriate to use the hypothesis that: the spatial autocorrelation of electric vehicle charging points is related to the road layout and traffic density gradient in a given area.

The research process in this article involved analyzing the general and detailed locations of electric vehicle charging points based on our own inventory, including field surveys and data from spatial information systems. ArcGIS tools, a specialized tool for analyzing data related to electromobility, were used for spatial data processing and interpolation analyses. For a more comprehensive depiction of the phenomenon, the Inverse Distance Weighting method was used to present the results in cartographic form, allowing for the presentation of both descriptive and geostatistical data.

Keywords: spatial interpolation, electromobility, electric vehicle charging points.

Introduction

The growth in electric car sales over the past five years has had a significant impact on the global automotive market. By the end of 2024, the number of electric vehicles reached nearly 58 million, representing approximately

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4% of the total passenger car fleet and almost three times the total number of electric vehicles in 2021. China, of course, leads the way in electric car usage, with one in ten cars on its roads being an electric vehicle [1].

Data shows that in 2024, almost half of car sales in China were electric, accounting for almost two-thirds of electric cars sold globally. However, looking at monthly sales, electric car sales have overtaken conventional car sales in the country since July 2024, increasing the share of electric car sales for the entire year to nearly 50%. This situation is intensifying the price competitiveness of electric cars, not only in China but also has consequences in other competitive markets [2].

The European market clearly differs from the Chinese market [3]. Here, the ratio of electric cars to conventional vehicles is one to twenty [4]. However, in 2024, it was recorded that every fifth new car sold on the European market was electric. The share of electricity sales increased in 2024 in 14 of the 27 EU Member States, while stagnation was recorded in the remaining countries. This result is undoubtedly influenced by the political sector, which calls for environmental protection and actions to reduce global warming [5]. However, despite everything, promotional campaigns by member states seem to be weakening, resulting in the withdrawal or reduction of subsidies for the purchase of electric cars in Germany and France. This situation may be related to the geopolitical situation related to the war in Ukraine or migration problems. However, looking at the UK market, one can notice that annual increases in electric car sales of almost 30% place this country among the leading areas with high electromobility intensity and demonstrate the tendencies of the modern digital society [6].

Norway is a unique example of electric vehicle sales in Europe. It has achieved almost complete electrification, with nearly 90% of car sales being electric, and just under 3% being hybrids. As a result of this high interest in electric vehicles, Norway's road fuel consumption in 2024 fell by almost 15% compared to 2021. Even finding rental cars powered by diesel or unleaded gasoline is a challenge. A similar trend can be observed in the Icelandic market, which is a model for pro-ecological behavior, from using natural heat for home heating to using battery-powered vehicles. This thesis is also supported by data from the International Energy Agency (IEA), which notes that the share of electric vehicles in leading markets, such as China, the United States, and Europe, is increasing annually [7] (Fig. 1).

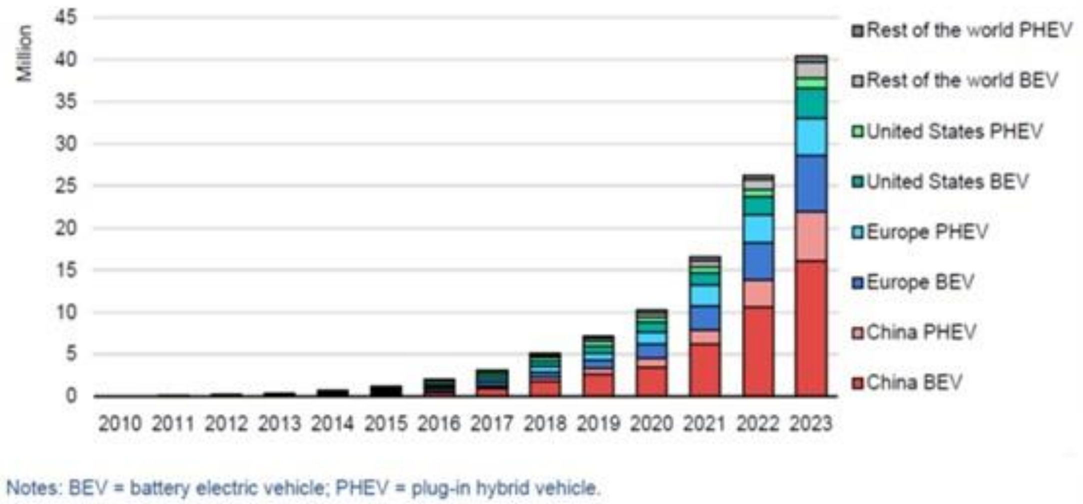

Figure 1. Trends in the global electric car market 2010-2023.

Source: Own study based on [7].

The above factors determine the emergence of innovative initiatives aimed at continuously promoting the reduction of greenhouse gas emissions [8] originating from transport [9]. In the context of preferences for counteracting this problem, the use of electric vehicles (EVs) is indicated in the context of transport tasks [10]. Such initiatives are referred to in the literature as electromobility, which encompasses all aspects of transporting people and cargo using electric vehicles.

Electromobility itself, in addition to battery-powered vehicles, is inextricably linked to road transport infrastructure, which includes: a charging zone consisting of one or more charging stations; a charging station, defined as a physical installation in a designated location; a charging point, also known as a charging station, a device that supplies electric vehicles with electricity; and a connector, defined as the physical interface between the charging or refueling point and the vehicle, through which fuel or electricity is exchanged.

The interpretation of the specified elements of charging point infrastructure in terms of transport infrastructure development can be found in the provisions of Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, abbreviated as AFIR (Alternative Fuel Infrastructure Regulation) [11]. The regulation entered into force in the European Union on 13 April 2024. Thanks to a certain standardization of terminology related to electromobility in road transport, the standardization of concepts, principles, and procedures has begun in the area of transport infrastructure adapted to the needs of low- and zero-emission vehicles. It should be noted that before the introduction of AFIR, the development of alternative fuel infrastructure, for example, was implemented freely by European Union Member States. This applies in particular to the implementation of electric vehicle charging points in urban and rural areas, which are crucial for electric vehicle users [12].
The dominant technologies here include solar technology, which charges the vehicle's batteries thanks to photovoltaic panels placed on the vehicle's roof, pantograph technology, induction technology, and standard wired technology [13]. It is worth mentioning that the charging point itself, as a device enabling the charging of a single electric vehicle, is defined in the Act of January 11, 2018, on electromobility and alternative fuels [14]. From a technological perspective, it is equipped with a specialized connector enabling the connection of an electric vehicle to an external energy source. Considering the location of vehicle charging points, it should be noted that it depends on a set of factors important for vehicle and road users, operators of point and linear transport infrastructure, transport, forwarding, and logistics companies, and companies implementing investments in the construction of alternative fuel infrastructure. Based on the above, charging points can be classified (Fig. 2.).

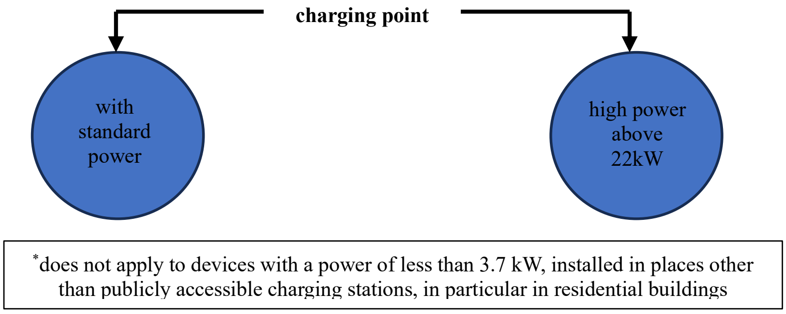

Figure 2. Classification of charging points.

Source: Own study.

In principle, the charging area itself, or the charging station, can be considered secondary, as vehicle users are primarily interested in the location and technology of charging points. Despite all the applications available on the consumer market, searching for information about the location of charging points and whether there is a need to build one in a given area remains a top priority. Based on the available literature on electromobility, it has been determined that key areas for assessing the usefulness of electric vehicle charging point locations include: charging point importance, spatial accessibility, and ease of use [15, 16, 17].

This has significant implications for the very nature of electric vehicle charging point deployment, not only in terms of the broadly understood development of electromobility but also in the context of the very concept of electric vehicle economics [18]. Therefore, with this in mind, research was conducted to assess gaps in spatial data, so-called "white spots," where a concentration of charging points either does not exist or is very small.

Research materials and methods

Considering the specific nature of implementing electric vehicle charging points in a given area, it can be seen that it results primarily from the road network in a given area, including vehicle traffic volume [19, 20]. It is also worth noting that, in terms of the country's spatial development, the idea of creating new charging points is consistent with the aspect of travel, i.e., the movement of people for various purposes [21]. This also stems from the fundamental maxim that also applies to road transport: „think globally and act locally". This is primarily to promote diverse forms of human movement, whether in the context of broadly understood tourism or in the aspect of developing ecological communication behaviors within road transport [22, 23].

This orientation creates opportunities to promote places that previously played a secondary role in communication systems, including in the transport industry. In order to identify gaps in the data, i.e., electric vehicle charging points, the study considered it appropriate to use the hypothesis that the spatial autocorrelation of electric vehicle charging points is related to the road layout and traffic density gradient in a given area. Initial work included familiarization with the location of electric vehicle charging points in Poland and Europe [24, 25]. Based on this, the research goal was formulated, which was to interpolatively estimate gaps in the spatial data of electric vehicle charging points in the Republic of Poland.

For the purposes of this study, the research process was divided into two stages:

- Stage 1 – involved determining the general and specific locations of electric vehicle charging points. The research process was based on our own field surveys, literature research, spatial information system databases, and analysis of planning documents and industry data.
- Stage 2 – comprised the selection of research tools and preliminary GIS processing of spatial data, i.e., geostatistical interpolation. The research employed the spline with barriers method. This method fits a mathematical function to a specified number of nearest points by passing through sample points [26, 27].

The study utilized data collected on the locations of electric vehicle charging points implemented in Poland, monitored between May and September 2025, from the following sources:

- The Alternative Fuels Infrastructure Register, maintained by the Office of Technical Inspection, which is the official, publicly available register of charging and refueling points in Poland. This data comes directly from station operators and is continuously updated;
- PlugShare, a popular global application with an interactive map and specialized filters related to the implementation of charging points;
- ChargeFinder, an application with an exported map of charging stations in Poland and abroad;
- Greenwaypolska.pl, Elocity, Naładuj.pl, Elektromobilni.pl, Stacjonat.pl, and PlugBox.eu, which are dedicated applications that provide the location of electric vehicle charging stations and points, as well as availability and current prices for electric vehicle users.

In this article, ArcGIS tools, a key tool in the analysis of data related to electromobility, were used to process the results, including generating data with final interpolation. Thanks to its spatial data implementation capabilities, the system can integrate location data with descriptive information to support the planning, optimization, and management of electric vehicle infrastructure.

In this study, the predicted cluster density of established (recorded) records at location (x, y) was used to generate the interpolation algorithm, which can be determined based on the following formula:

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} \left[\frac{3}{\pi} \cdot pop_i \left(1 - \left(\frac{dist_i}{radius} \right)^2 \right)^2 \right]$$

$$for\ dist_i < radius$$

where:

$i = 1, \ldots, n$ - entry points, taken into account only if they are within a radius of the location *(x,y)*.
pop_i - the value of the population field at point i, which is an optional parameter.
$dist_i$ - distance between point i and location *(x,y)*.

The calculated density was multiplied by the number of points in the generated area, the voivodeship (administrative unit). This correction affects the value of the integral in the generated interpolation area, which is equal to the number of points (records) or the sum of the population area, although it is not always equal to 1. This implementation uses the Quartic clustering function. This value had to be calculated for each location where density was estimated.

Due to the relatively complex interpolation procedure, the study assumed that a smooth, curved surface was fitted to each point. The surface value is greatest at the point location and decreases as the distance from the point increases, reaching zero at the distance from the point. Only circular neighborhoods are possible. Because a raster image is created for interpolation, the density in each cell of the resulting raster was calculated by adding the values of all cluster surfaces where they overlap at the center of the raster cell. The work was preceded by an analysis of literature studies and spatial data related to the geolocation of electric vehicle charging points in Poland, which are shown in the figure below (Fig. 3).

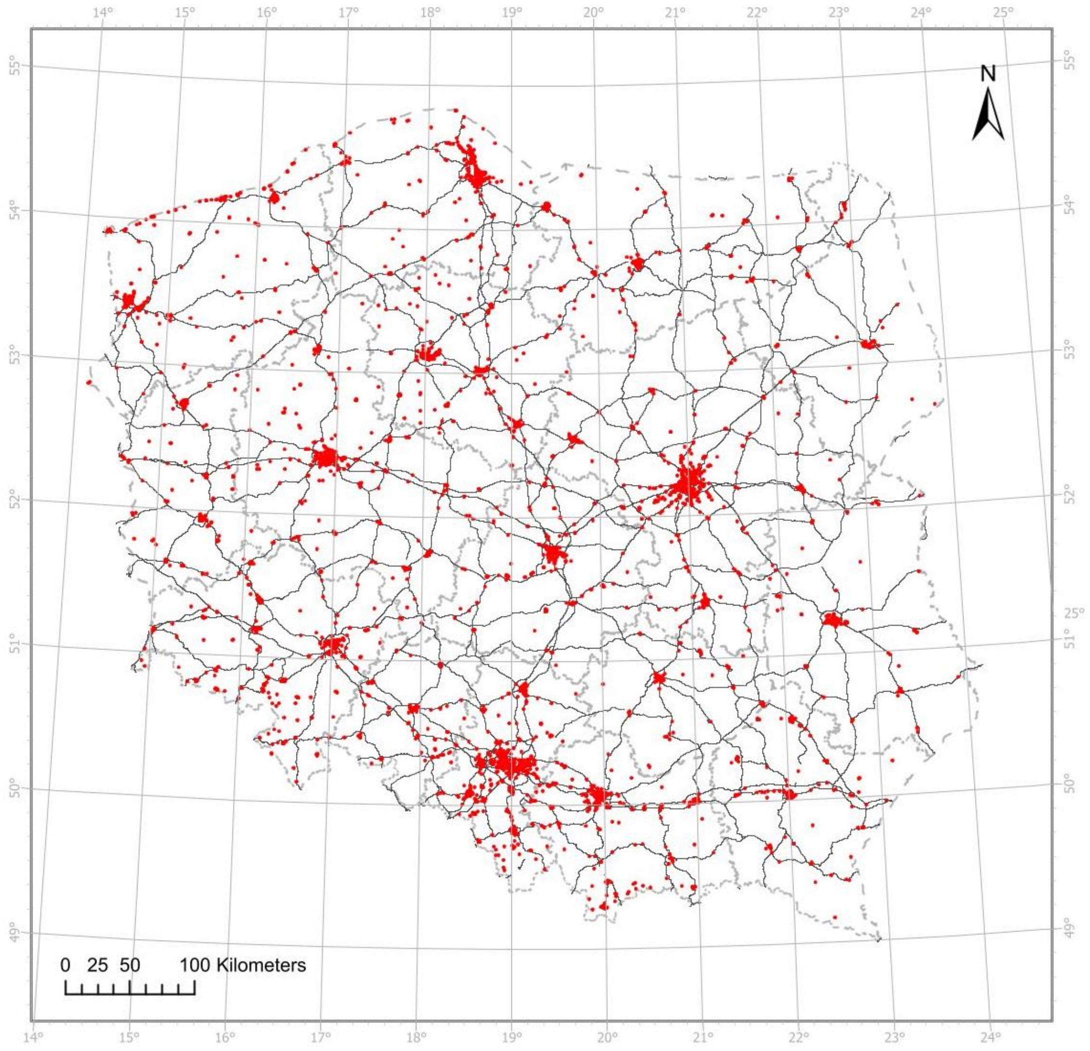

Figure 3. Location of electric vehicle charging points in Poland.

Source: own study.

Spatial interpolation of gaps in the data of electric vehicle charging points in Poland.

The spatial distribution of electric vehicle charging points should be considered in terms of many variables, including: proximity to the road network, border crossings, transfer hubs for employee traffic, proximity to logistics hubs, and general accessibility to industrial parks. When analyzing the concentration of charging points in Poland, preliminary estimates should begin with examining the volume of vehicle traffic, which is obviously due to the movement of cargo flows, but one should not forget about the ordinary mobility of people who travel every day to their places of work, taking children to school, or buying supplies in nearby shops, etc.) [28]. This process results from the consolidation of knowledge about transport propensities and the performed transport tasks from an economic perspective. Vehicle traffic intensity is here a determinant of the creation of new charging points, which are associated with generating income from the location, constituting a kind of location rent, or location rent.

With the collected research material at our disposal, the concentration of charging points for electric vehicles was determined by generating polygonal centroids of data from the representation of charging point locations in Poland (Fig. 3.). Based on the obtained structure, a heatmap interpolation was performed, which provided an image of the occurrence of specific points with similar characteristics, constituting a concentration of charging points with a specific saturation. (Fig. 4.).

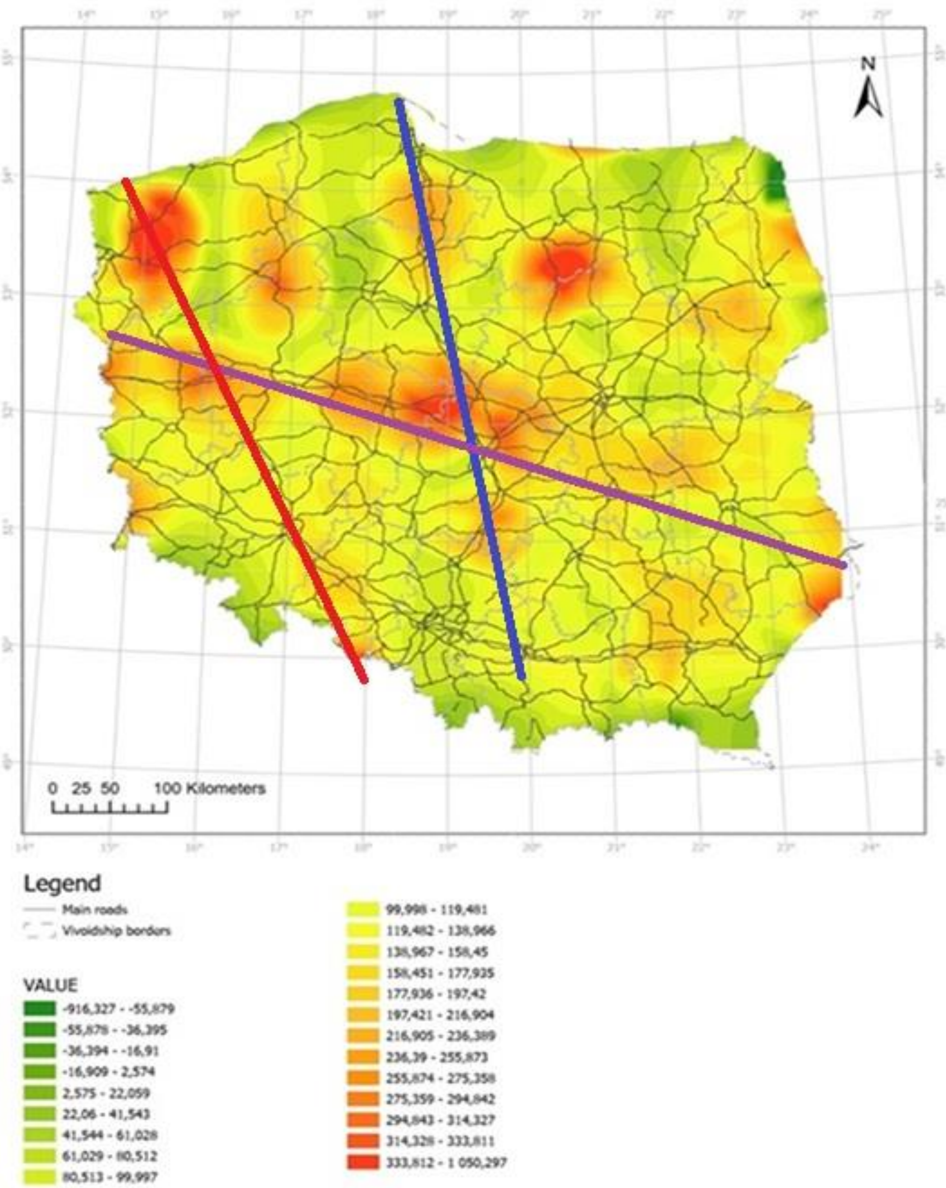

Figure 4. Concentration of electric vehicle charging points in Poland in 2025.

Concentration of points in the direction: foreland of the Gdynia-Gdańsk seaports – Adriatic Sea, Aegean Sea,
Concentration of points in the direction: foreland of the Świnoujście-Szczecin seaports – Adriatic Sea, Aegean Sea,
Concentration of points in the direction: foreland of the Rotterdam port – Eastern Europe, Asia.

Source: Own study.

The presented geostatistical analysis shows that the concentration of electric vehicle charging points aligns with the directionality of the Trans-European Transport Network (TEN-T), which includes road, rail, air, sea, and river routes. These elements are the most important determinants of freight movement and also constitute point elements of road infrastructure [29]. Due to Poland's location in Europe's spatial system, the meridional directionality of transport dominates in the European Union's key roads, which aims to ensure full territorial cohesion of the European Union and facilitate the free movement of people and cargo from the far north of Europe to the south and from the west to the east. Of note here is the use of sea routes, which have led to the emphasis on the role of seaports in the entire supply chain. [30].

The saturation of charging points depends on the road network, although it's worth noting that charging points are also quite dispersed. This fact highlights the important fact that electromobility in Poland is a heterogeneous phenomenon that is constantly evolving. The increased focus on charging point implementation can be identified with three directions of freight and population movement:

- Direction 1: Gdynia-Gdańsk seaports – Adriatic Sea, Aegean Sea,
- Direction 2: Świnoujście-Szczecin seaports – Adriatic Sea, Aegean Sea,
- Direction 3: Rotterdam ports – Eastern Europe, Asia.

The above indicates that seaports play a significant role in the movement of cargo, serving as transshipment hubs connecting continents, countries, and metropolitan areas with high industrial intensity. Considering the point-by-point system, border crossings, primarily in the eastern regions, play a significant role in the overall system: Korczowa-Krakowiec, Medyka-Szeginie, and Hrebenne-Rawa Ruska, which serve as road junctions with branches to the Black Sea and the Aegean Sea. Looking westward, the Port of Rotterdam undoubtedly plays the most important role at present, as, in addition to its crucial transshipment functions, it also plays a significant strategic role in ensuring an adequate level of security in Europe. The directions identified above are not only important sections of European transport corridors but also significant directions that reflect the intensity of population movement in terms of tourism. They also show significant gaps in the spatial data, which are highlighted in green in the figure above, also indicating the lowest intensity of charging point distribution.

For a more complete illustration of the phenomenon, the obtained results were verified using the Inverse Distance Weighting method for spatial analysis, which takes into account the weighted averages of the values measured at points near the interpolation points as the basis for interpolation [31]. The results, interpolation using the IDW method are presented in Figure 5.

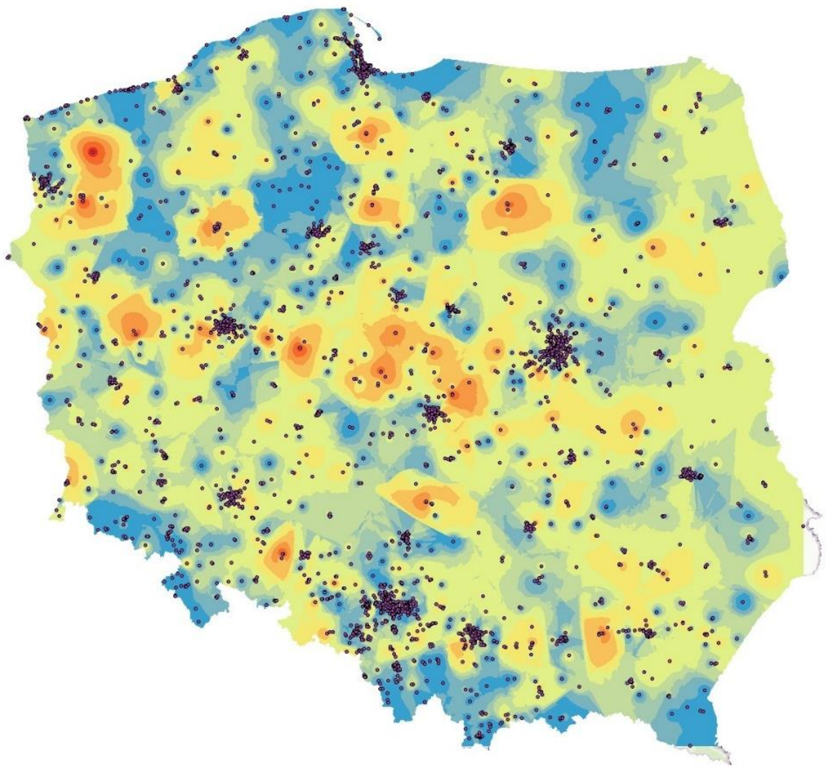

Figure 5: Spatial interpolation of electric vehicle charging points in Poland in 2025 – Inverse Distance Weighting method

the largest concentration of vehicle charging points,
moderate concentration of electric vehicle charging points,
the lowest concentration of electric vehicle charging points.

Source: Own study.

Analyzing the spatial interpolation of charging points presented above, it can be concluded that one of the main drivers of the creation of new charging points are major cities, serving as metropolitan cities, such as Szczecin, Gdańsk, Katowice, Łódź, Bydgoszcz, Wrocław, Poznań, Warsaw, Rzeszów, Lublin, and Białystok. This aspect decisively influences the overall development of electromobility in these subregions. Within these metropolises, there are also important logistics hubs, which have a significant impact on the mechanism for the creation of new charging points.

Seaports, crucial to the national economy in Poland, are also significant drivers of the construction of new charging points. These include, in particular, the Świnoujście-Szczecin and Gdynia-Gdańsk complexes. Thanks to these massive transshipments, new transport corridors are being created, but they also become a bridge connecting other transport hubs, such as the Central European Logistics Hub – the largest warehouse in Poland – and the Silesian-Kraków Industrial District.

Analyzing the spatial interpolation illustrated in Figure 5, attention is drawn to the blue spots, which are more or less intense throughout Poland. They are visible along the entire coastline from Świnoujście to Krynica Morska and further from Krynica Morska to Wisztyniec, the tripoint where the borders of Poland, Russia, and Lithuania converge, but also across the entire mountain ranges in southern Poland. Recreational areas would seem to be the basis for creating new charging points, but it should not be forgotten that 23 national parks also occupy high-density areas: Babia Góra, Białowieża, Biebrza, Bieszczady, Tuchola Forest, Drawieński, Gorczański, Góry Stołowe, Kampinoski, Karkonosze, Magura, Narwiański, Ojców, Pieniny, Polesie, Roztocze, Słowiński, Świętokrzyski, Tatra, Ujście Warty, Wielkopolski, Wigry, and Wolin. These areas are excluded from any major industrial activity, including the implementation of charging stations.

The same applies to the Great Masurian Lakes area, located in the Warmian-Masurian Voivodeship, and the Kashubian Lakes area, located in the Pomeranian and Kuyavian-Pomeranian Voivodeships. These areas have the fewest charging stations, despite being very popular recreation areas.

Additional obstacles to implementing charging points are national security concerns, particularly the presence of military units and military training grounds, which occupy vast areas.:

- Drawsko Pomorskie Training Area – 32.8 thousand ha,
- Wicko Morskie Training Area – 2.3 thousand ha,
- Toruń Training Area – 12.2 thousand ha,
- Bemowo Piskie Training Area – 16.7 thousand ha,
- Nadarzyce Training Area – 8.1 thousand ha,
- Świętoszów-Żagań Training Area – 35.9 thousand ha,
- Nowa Dęba Training Area – 15 thousand ha,
- Lipa Training Area – 12 thousand ha.

Considering the existing data gaps, marked in blue in Figure 5, the southern region also attracts attention. Despite the presence of many areas with high investment and industrial intensity, such as the Upper Silesian Industrial District, the Kraków Industrial District, the Opole Industrial District, and the Wrocław Industrial District, mountain ranges pose a natural obstacle to concentrating charging points there.

Conclusions

To summarize the previous considerations, it should be noted that spatial estimation is used in many different areas of human life [32]. However, very few studies address its application in spatial analyses in the area of electromobility. Location modeling of electric vehicle charging points is an innovative approach that is worth developing and highlighting implementation niches related to variables that influence the overall model form of the entire electromobility-related infrastructure.

The model itself of the dependence of the transport infrastructure for electric vehicles, marked as an endogenous variable Y from the previously presented elements (loading zone – X_1, charging station – X_2, charging point – X_3, connector – X_4), constituting potential exogenous variables defined for a given area (e.g. voivodeship or country) can be written as follows:

$$Y = f(X_1, X_2, X_3, X_4) + \xi$$

The symbol f denotes a specific analytical form of the variable function , which can be treated as elements of potentially changing infrastructure parameters of the road transport network for electric vehicles, which may appear during the monitoring period t, which is a time variable that appears unexpectedly [33, 34].

The symbol in the formula represents the so-called random component of the model, which represents the combined effect of all factors explicitly included as explanatory variables in the model on the endogenous variable

Y [35]. In our case, the random component measures the deviation of the empirical distribution values from the theoretical distribution [36, 37]. Semantically, it represents a set of external and internal factors that, in a given situation and time, influence the overall form of the analyzed function. The random component here counterbalances the formation of a core concentration of charging points, which was observed during the research.

Modeling the surface representing the density of activities in the field of electromobility allows for the determination of the interdependencies between the electric vehicle charging system, which is still under construction and development in Poland. The use of kernel estimation for spatial analysis of electric vehicle charging points can also involve not only assessing density, but also assessing the intensity and concentration of a given economic phenomenon related to the transport of people and goods.

The analysis of the phenomenon shows that the electromobility phenomenon in question, illustrated in Poland by showing data gaps, or "blue spots," indicates the need to take into account the differential terrain model and environmental conditions, which are crucial in implementing new charging points.

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