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Management of the modern electric-vehicle market

Abstract: This paper proves that the trend of development of modern transport in the world is to maximize the level of providing the personal use of electric vehicles. This mechanism would also partially solve the environmental problems of mankind. To implement this idea, some global automakers have announced the decision of the full transition of production to electric vehicles. At the same time, for effective functioning of the electric-vehicle market, adequate infrastructure needs to be created. There is a positive trend in the annual growth of the charging-station network in developed countries, that characterizes the charging-station market as dynamic and promising, but mostly chaotic and imbalanced at the regional level.

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The main hypothesis of the research is about the independence between the level of electric-vehicle market development and networks of charging stations. The object of the study is the Washington (USA) electric-vehicle market, as it is the market segment with the highest development characteristics.

To test the hypothesis, the authors provided a multifactor analysis of the local electric-vehicle market and the existing charging infrastructure. A comprehensive analysis of the electric-vehicle market and the charging-station network in Washington (USA) was performed, and the market characteristics were defined accordingly: the degree of electric-vehicle spread in the regional localities; the level of charging-station-network coverage and concentration; the ratio of electric vehicles to charging stations.

Authors identified the tendency of the state location to innovations connected with electric vehicles. Clusterization and recommendations according to the level of development of the electric-vehicle market aimed to balance and grow the total electric-vehicle market and connected infrastructure.

KEYWORDS: electric vehicle, USA, locality, electric-vehicle market, charging station

List of abbreviations and transcript

EV – electric vehicle. The current study has only examined vehicles powered by an electric motor with an electric battery installed as the main battery.

CS – charging station. The study considers different types of charging stations, including DC Fast, Level 1 and Level 2, as further discussed in the article.

IL – inhabited locality.

Introduction

Nowadays, the world is changing dynamically due to scientific and technological progress intensively penetrating every human activity. Outdated technologies are losing relevance and are being replaced by modern, environmentally friendly, progressive, and innovative means of production, which significantly facilitates quality of life and increases production efficiency. The electric-power industry, which is considered a conservative industry, has not become an exception regarding the above-mentioned tendencies, which are required to ensure the environmental friendliness of the electricity-production processes, and to provide options for their accumulation and rational use. Thus, introducing alternative energy sources and the spread of rechargeable batteries, smart grids, etc. are considered promising development directions today.

Throughout its history, the electric-power industry has been considered a cross-sectoral phenomenon able to enhance the rapid development of transport, information and communication, engineering, and other sectors of the global economy. Thus, the transition to electric motors in the transport industry was a sign of a fundamental shift in the principles and traditions underlying the industry's operation, which have evolved over a considerable time and are still being applied. The reasons for this transformation include specific properties of electricity, its technological and technical limitations, while the results imply a comprehensive shift in approaches to organizational, infrastructural, logistic, technological, and other aspects of using electricity.

The modern global trend for electrified transport is striving to meet the population's demand for personal EVs, which would partially solve the associated environmental problems. In order to achieve this goal, the world's leading automakers, such as Jaguar (Jaguar official 2021) and Ford (Ford official 2021), announced a decision to switch solely to EV production in the near future. Whereas Volkswagen (Volkswagen official 2021) set a goal to reach at least 50% of EV sales by 2030. Every new day witnesses transformations in the EV market, and in 2021, the volume of EV sales in the world has grown more than two times compared to the previous year and reached 6.6 million units or about 9.0% of the world car market (Paoli 2022). At the same time, China sales reached 3.4 million units in 2021, European countries had sales of 2.3 million units and the United States had sales of 0.5 million units; these are among the top three in terms of global EV market growth.

However, even though such a revolutionary direction is accepted by the automakers, the overall realization of the stated goal can only be possible in practice on the condition that an appropriate infrastructure is created, specifically a CS network, without which EV production is either irrational or even unjustified. At the same time, studies of CS infrastructure development indicate significant problems in this area, such as the CS network being insufficient or scarce even in developed countries, CS chaotic territorial distribution, as well as the need for architectural changes being introduced by the building owners, utilities and designers (Efthymiou et al. 2017; Goswami et al. 2020; Hardinghaus et al. 2020; Metais et al. 2022; Petratos et al. 2021; Shanti et al. 2020). The above-mentioned issues evoke drivers' concern related to stable access to facilities to charge the EV's battery during its active operation. Therefore, these issues constitute a significant factor limiting the demand for EVs.

Simultaneously, we can observe a positive trend of annual CS network and coverage growth in developed countries, which is significantly facilitated by governmental support programs aimed at the CS sector enhancement. Thus, the CS market can be considered to be dynamic and promising, although its growth is overly chaotic and requires formalizing the development vectors. Consequently, in-depth studies are needed to establish the degree of compliance between the infrastructure support and the quantitative composition of the global EV market, which should become the basis for developing a strategy for a balanced, interconnected, and unidirectional vector of development of the EV market and CS networks. Thus, the above-mentioned factors explain why the chosen research topic is **relevant**.

The hypothesis that will be tested is that there exists no relationship between the stage of the EV market development and its infrastructure support provided by CS networks. This means the

chaotic and unregulated development of market components, which may result in a slowdown of electrified transport and a reduced demand for EVs among the population.

In order to test the hypothesis, the infrastructure of the US EV market was chosen as the object of study. This choice is explained by the fact that, firstly, the United States is among the top three world leaders in EV sales; secondly, the country has a long history of encouraging consumers to use EVs. Tax incentives and subsidy programs were introduced in the country in 2009 in response to the 2008 crisis, whereas China introduced such measures only in 2014 (Scaling Up 2020). In addition, in the early 2021, the United States launched a plan to develop the infrastructure of the EV market through implementing a complex of grants, tax rebates, marketing benefits and material incentives aimed at establishing at least 500 thousand CSs (Policies 2022). Assessing the results and the efficiency of the measures implemented to stimulate the development of the EV market infrastructure in the United States should substantiate and formulate specific recommendations for balancing EV market trends in some US states, as well as in some other regions of the world, where the pace of EV market development and its infrastructure lag far behind those inherent in the world's leading countries. In addition, both the best practices and problematic aspects of the trends in the infrastructure of the EV market in the United States identified in this study should underlie national roadmaps and relevant innovative projects to promote electric electrified transport in the world in order to reduce CO_2 emissions and gradually improve the environment.

1. Literature review

In considering the relevance of the infrastructure support problem for the EV market functioning, we performed a quantitative analysis of the total number of works published on this topic using the database search service (Scopus 2021). Figure 1 demonstrates the obtained results.

The analysis highlights the trend of annual increases in the volume of research works devoted to the functioning of the EV market, simultaneously demonstrating that the number of works devoted to EV prevail (in 8–15 times) over the number of studies describing the infrastructure. The obvious imbalance between the research topics can be explained by the greater potential and better prospects for developments in the EV field, which may be funded by large auto giants, whereas the same funding volume cannot be involved while studying service infrastructure elements. However, given the fact that it is impossible to implement the strategy of a balanced EV market development without appropriate infrastructure, the scientific community should assign more attention to the development of CS networks.

Recent evidence from studying examples of different territories suggests several general conclusions can be drawn with regard to EV market trends. Thus, the state of EV market functioning in the United States has been investigated and economic and mathematical forecasts for its prospective growth in terms of basic economic and social factors have been carried out (Sotnyk
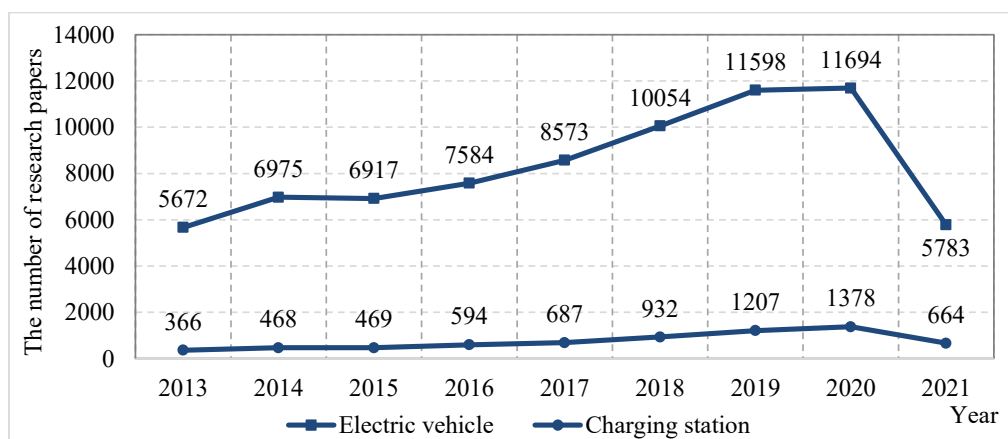
Fig. 1. Dynamics of the number of research papers published on EV and CS (composed by the authors)

Rys. 1. Dynamika ilości opublikowanych artykułów naukowych na temat EV i CS

2020). An in-depth study of CS quantity that the market would need for effective EV exploitation in European countries has proven that additional progress can be ensured exclusively through the corresponding development of infrastructure support (Mathieu 2020). The distribution of EVs in large cities of the world and the CS number necessary for their functioning have been analysed, which has revealed an uneven development of the EV market in the cities and explicated the need to devise an action plan to address the imbalance issue (Hall 2020). Spöttle (2018) used a complex survey to assess both the quantitative and qualitative composition of the CSs required to service the existing EV fleet in Europe based on a differentiated approach to regulatory indicators in European countries. The same publication contains recommendations for implementing corrections in the energy policy of the respective countries. The developments described above prove the relevance of the chosen research topic and serve as the methodological background for this study.

In addition, attention should be paid to recent research in the field of infrastructure support of current trends in the EV markets of different countries. The value of research lies in the methods and practical tools that researchers propose to justify the prospects for the sustainable development of CS and EV infrastructure. For instance, in order to substantiate the necessary and sufficient CS city network, D. Efthymiou, K. Chrysostomou, M. Morfoulaki (2017) proposed a genetic algorithm created in R language. The Greek city of Thessaloniki was selected as the territorial object of the study, where, at the time of article publication, EVs were practically absent. The authors based their forecast on the assumption that in the near future, EVs will replace gasoline vehicles being used in the city at the time. R. Goswami and G.Ch. Tripathi (2020) worked on similar issues and reviewed the approaches to determining the need for India's charging infrastructure development provided that the government's goal to achieve a 30% share of the EV market is realised by 2030, although the current level does not exceed 5%.

Arakawa (2018) employed a multi-period model and analysed the impact made on the EV expansion trend in the country by the development of charging infrastructure and government subsidies assigned to the consumers on the purchase of an EV. The author argues that subsidies are a significant factor stimulating innovation in the technology of increasing the capacity and reliability of batteries, which significantly and positively affects the consumer demand for EVs. While justifying the optimal plan for the CSs' location within the city, Metais et al. (2022) recommend taking into account three key factors, namely, economic, technical and consumer behaviour. The authors analyse the existing methods of building CS networks in a certain area, which differ in the degree of response to certain factors of influence and emphasize the necessity to consider the time factor. Using CS coverage in Berlin as an example, Hardinghaus et al. (2020) demonstrate approaches to the optimal creation and exploitation of charging infrastructure both in the city centre and in the outskirts. Infrastructure efficiency, the cost of services and user demand were chosen as the criteria for the survey. Voronoi polygons, the Gini coefficient and special coefficients were used as analysis tools.

Petratos et al. (2021) used the Reinforcement Learning program to optimize the CS network location in a particular area by calculating EV traffic, registered number of EVs and the architectural features of the city.

Shanti et al. (2020) formulated approaches to modelling EV managed charging, which will be aimed at minimizing the requirements to modernise the existing city infrastructure and optimise peak energy demand. Implementing this approach is aimed at reducing the city's needs for constructing CSs, which should make the EV owners' lives easier and increase the demand for EVs among the population.

Each of the mentioned scientific papers has contributed to the development of EV charging infrastructure; however, this issue has not been fully resolved and requires further in-depth research in order to develop recommendations for balancing the EV market in a particular area.

2. Methods and methodology

In order to test the hypothesis, the study uses a multifactor analysis of the local EV market and the existing infrastructure to determine the adequacy of the CS network growth rate in a given area to the EV ownership level among the population. The local EV market in Washington State was chosen as the object of the study because this market segment is developing most dynamically today and may become a reference point for other states and regions of the world. As an empirical basis for the study, the authors selected open databases on various aspects of the EV market in 363 ILs in Washington State, USA. The objectives to be achieved by this research are as follows:

◆ to conduct a comprehensive analysis of the EV market and the network of CS distribution in Washington State, USA according to the following main characteristics: EV ownership in the cities of the region; the level of CS network coverage of the state's territory; territorial concentration of the CS infrastructure; the ratio of EVs to CSs in a given area;

◆ to determine the predisposition of the relevant ILs to innovate; the level of EV usability in certain ILs in the state; EV market balance of the territory;

◆ to cluster ILs according to the level of EV market development taking into account the above-mentioned criteria; to describe the EV market development in each cluster; to substantiate recommendations on the feasibility of implementing specific measures to balance or expand the EV market within each cluster.

When constructing a sequence of procedures for analysis in this study, the method of logical generalization was used. To demonstrate the prevalence of the selected research topic, the dynamic series method was used, with which we processed the data obtained from the Scopus database search service (Fig. 1).

In order to illustrate the database generated for the research, due to its excessive volume, the method of selective presentation was applied, for which five ILs with the highest and lowest characteristics of the local EV market were selected (Table 1). A Ranking method was used as an aid to identify which ILs may be considered leaders and outsiders in relation to the EV market trends according to the selected indicator from the data set.

A comprehensive quantitative analysis of the local EV market functioning in all the ILs located within Washington State was carried out using three relative indicators, for each of which, the evaluation criteria have been substantiated further in the article: the ratio of EV to CS numbers (EV/CS ratio); coefficient of EV ownership; CS location density factor.

The obtained calculation results are presented in the tables with indicators of descriptive statistics, such as minimum, maximum and mean value of the series; the number of observations that is higher, below or corresponding to the required level; the number of observations corresponding to the optimal level (Tables 3–5). The mathematical model (1–2) is substantiated, which combines three indicators selected for research, the optimal values are also specified.

Visualisation of the IL's geoinformation location with the optimal and required levels of the calculated value for a certain indicator in Washington State was carried out using the free QGIS software package (Fig. 3). Graphical and comparative research methods were employed to assess such characteristics of the EV market as infrastructural insufficiency or surplus (Fig. 4). The comparison was made based on the EV/CS ratio calculated for the ILs under study, countries and large cities of the world, which was followed by comparing the obtained values with the optimal ratio level and the required value range.

The clustering of 129 ILs in Washington State was performed using data obtained from the calculations of three indicators by the k-means method and Euclidean metrics using the analytical service, Science Hunter (Science Hunter 2021). The clustering criteria included the sum of the squared errors index, the Trace index, the Dunn index, the Davies-Bouldin index (DBI), the Calinski-Harabasz index, and the PBM-index. The tools of the Science Hunter service (Science Hunter 2021) illustrated the spatial arrangement of the clusters obtained by calculations (Fig. 6).

A detailed description of the characteristics of each of the eight selected clusters is provided. For those ILs that fell into a particular cluster using the method of expert evaluations, the authors have formulated basic recommendations to balance the EV market.

3. Presentation of the main material

The research procedures were sequenced in accordance with the scheme shown in Figure 2.
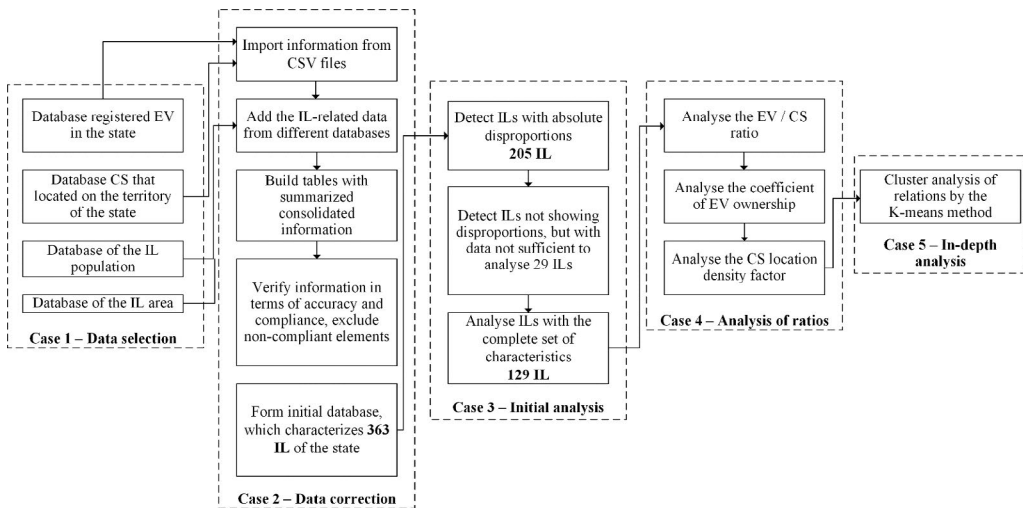

Fig. 2. Research procedure implemented in the study (composed by the authors)

Rys. 2. Procedura badawcza wdrożona w badaniu

The methodology of the study involves gradual implementation of five consecutive cases. At the initial stage **(Case 1)**, publicly available information was collected and systematized, which provided a comprehensive quantitative description of the EV and CS market in Washington State. Additionally, at the same stage, information on the population and area of the IL was systematized, which would serve to compare territories by specific indicators in the context of the study. Based on the results of systematization of the source information, at the stage of data adjustment (**Case 2**), consolidated information on the functioning of 362 ILs of the state was structured in a tabular format.

This data block characterises various aspects related to the ILs. In particular, it includes information on: the name of the IL, the number of registered EVs and CSs, the population in 2019 (Census Bureau USA 2019) and the area of the IL in 2010 according to the Census Bureau USA National Agency (Census Bureau USA 2010). Information on electric cars includes a set

92

of vehicles with an electric motor which were registered in the IL at the beginning of 2021 (Washington 2021); data on the CS contains the total CS number designed for quick recharging of electric cars batteries, in particular: CS DC Fast, Level 1 and Level 2 (US Department of Energy 2021). Due to the excessive amount of information obtained, a section of the relevant data on ILs will be presented in this article by selecting five IL with the largest EV numbers and five IL with the smallest EV numbers (Table 1). The ranking in the table is based on the third column, which contains data on the number of EVs in the IL.

TABLE 1. Initial data on the studied inhabited locations of the state

TABELA 1. Wstępne dane o badanych regionach państwa

No	Name of the IL	Number of EVs [units]	Number of CSs [units]	Population [persons]	Area of the IL [km²]
1	Seattle	9 717	369	753 675	83.94
2	Bellevue	3 011	137	148 164	31.97
3	Redmond	2 298	30	71 929	16.28
4	Kirkland	1 796	36	93 010	10.79
5	Sammamish	1 698	8	65 892	18.22
…	…	…	…	…	
358	Townsend	1	0	-	6.98
359	Valley	1	0	-	0.43
360	Waldron	1	0	-	–
361	Warden	1	0	2 812	2.58
362	Wishram	1	0	–	1.28

Composed by the authors.

A thorough critical analysis carried out at the third stage of the study **(Case 3)** revealed such imbalances in the EV market development that further limited our calculations and, as a result, ILs were excluded from the calculations:

1. Seven ILs have one or two CSs, provided that there are no officially registered EVs in their territory. Mostly, these ILs are small and they are located along the coast and have acquired a resort and recreational orientation, which explains the fact of owing CSs. The EV market development strategy in these ILs should be focused on increasing the local population's interest in buying EVs, which should be based on the strategy of the corresponding region's environmental rehabilitation.

2. 205 ILs in Washington State demonstrate absolute market disparities due to having registered EVs (from 1 to 202 units at their average number of 20 units per IL) and a complete absence of public CSs at the same time. The absence of the CS network causes significant inconvenience to EV users and forces them to recharge cars only in places equipped with a charger (place of residence, parking at workplaces, etc.). Such circumstances significantly

limit the demand for EVs among the population of the mentioned ILs. In order to meet the EV users' needs, balance the market and improve the environmental situation in the region, it is necessary to introduce effective tools to stimulate businesses to build CSs at the local level. The range of possible incentive tools may include large-scale informational and educational campaigns informing individuals and businesses of the state of EV market development and the benefits of using EVs, as well as attracting government subsidy programs.

3. Twenty-nine ILs do not have significant disparities in the EV market development. However, in statistical terms, they face technical limitations related to the lack of comprehensive information on the IL's population or area.

A necessary condition for harmonious EV market development should be the appropriate infrastructural support for the available registered EVs in the territory. In order to establish the level at which this condition is satisfied, **Case 4** provides a calculation of the relative characteristics of the EV market and the number of CSs for each of the ILs. Those 129 ILs of Washington State, for which **Case 3** proved that the requirement for disproportion absence had been fulfilled, served as the basis for the analysis of relative indicators. The following indicators were selected as relative indicators that should provide a comprehensive analysis of the EV market functioning in a certain territory:

1. **Ratio of EV/CS number reflects the number of EVs per 1 CS within a specific territory and is found by the formula:**

$$\mathrm{K}_{EV/CS} = \frac{N_{EV}}{N_{CS}}$$

where:

$\mathrm{K}_{EV/CS}$ — the ratio of EV and CS numbers, where: $\mathrm{K}_{EV/CS} > 0$,

N_{EV} — the number of EVs, registered in the territory of the IL in units, where $N_{EV} \in Z$ and $N_{EV} > 0$,

N_{CS} — number of CSs, located in the territory of the IL in units, where $N_{CS} \in Z$ and $N_{CS} > 0$.

This indicator is most frequently used in market assessment procedures by scientists and expert institutions (Mathieu 2020; Hall and Lutsey 2020; Hall 2020; Spöttle 2018), and is accepted as a criterion for evaluation and comparison in legislative acts (e.g. EU Directive 2014).

Spöttle (2018) conducted a study of possible ratio values, and determined that for effective EV market functioning, the ratio value should correspond to a certain minimum allowable level. Additionally, depending on the goals and initial conditions underlying the study, there are different levels of the sufficiency criterion, namely, the EV/CS ratio may vary from 7 (loyal criterion) to 27 (strict criterion) EVs per one CS built on the territory (Table 2).

Analysis of the ratio calculation method proves that its values may fluctuate within the range $(0; \infty)$. According to the consolidated opinion of experts, only certain intervals within a certain range can be effective. Thus, based on prevailing estimates, the interval of 8–15 EVs per 1 CS constitutes the minimum allowable, whereas the value of 10 EVs per 1 CS is considered as the

TABELA 2. Wartości współczynnika wystarczalności EV/CS na badanych regionach

Indicator level	Source
7–14	Cooper and Schefter 2017
8–15	Recommendation of the Chinese National Development and Reform Commission (NDRC)
From 8 to 15	The IEA Electric Vehicle Initiative
10	Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels
24	Wood et al. 2017
27	California Energy Commission and National Renewable Energy Laboratory 2017

Composed by the authors on the basis of (Spöttle 2018).

optimal number. This approach is rational given the views of the scientific community according to Table 2. At the same time, deviation of the ratio value towards a level higher than optimal indicates the insufficient ability of CS infrastructure to meet EV owners' needs, while its deviation towards a lesser value indicates an excessive amount of infrastructure, which is economically impractical.

The EV/CS ratio value is influenced by a significant number of factors, such as: the level of consumer demand for EVs in the region; the effectiveness of explanatory programs facilitating EV use, EV's cost-effectiveness, environmental friendliness and purchase feasibility; socio-economic programs implemented at the state and the local level, which are aimed at increasing EV ownership among the population through price adjustments or compensatory financial instruments; EV user satisfaction with the CS service; the policy on the expediency of EV and CS distribution adopted by automobile manufacturers, private business, local and state authorities. The list of factors affecting the ratio value is far from exhaustive; nonetheless, adjusting the ratio to the optimum level by various instruments should become the key to market efficiency.

The analysis of the statistical database on the EV market for the selected 129 ILs of Washington State proved territorial heterogeneity regarding the values of the studied indicator (Table 3). In general, 42,692 EV units are registered in the indicated ILs against 1 581 operating CSs, thus the average indicator value is 33.65.

The ILs with the optimal and required ratio level are located on the map in Figure 3.

The map shows that the ILs, for which the ratio value corresponds to the optimal or required levels, vary in size and are located throughout the state, most often in the vicinity of important highways and waterways. At the same time, it would be premature to conclude that there is a close relationship between the IL's location and the corresponding ratio.

In summary, Table 3 demonstrates that the EV markets in the majority of the studied ILs are unbalanced: given the constant EV amount, there is a need to increase the number of CSs by 67.0%, while 45.0% of ILs have an excessive level of CS availability.

Correlation-regression analysis tools allowed us to establish the vector of dynamics and the impact force affecting the variation in the EV/CS ratio value within the actual IL's area. The pur-

Table 3. Characteristics of the IL's by the value of the ratio of EVs to CSs

Tabela 3. Charakterystyka IL według wartości stosunku EV do CS

Indicator value	Name of IL	Indicator value	Number	%
Maximum	Camas	379.00	1	–
Minimal	Ritzville	0.34	1	–
Total number of ILs	–	33.65	129	100.0
Number of ILs with a ratio exceeding the required level (lack of infrastructure)	–	59.00	67	51.9
Number of ILs with a ratio corresponding to the required level (but not optimal)	Spokane, Ephrata	–	15	11.6
Number of ILs with a ratio corresponding to the optimal level	–	–	2	1.6
Number of ILs with a ratio that is lower than necessary (excessive amount of infrastructure)	–	4.00	45	34.9

Composed by the authors.

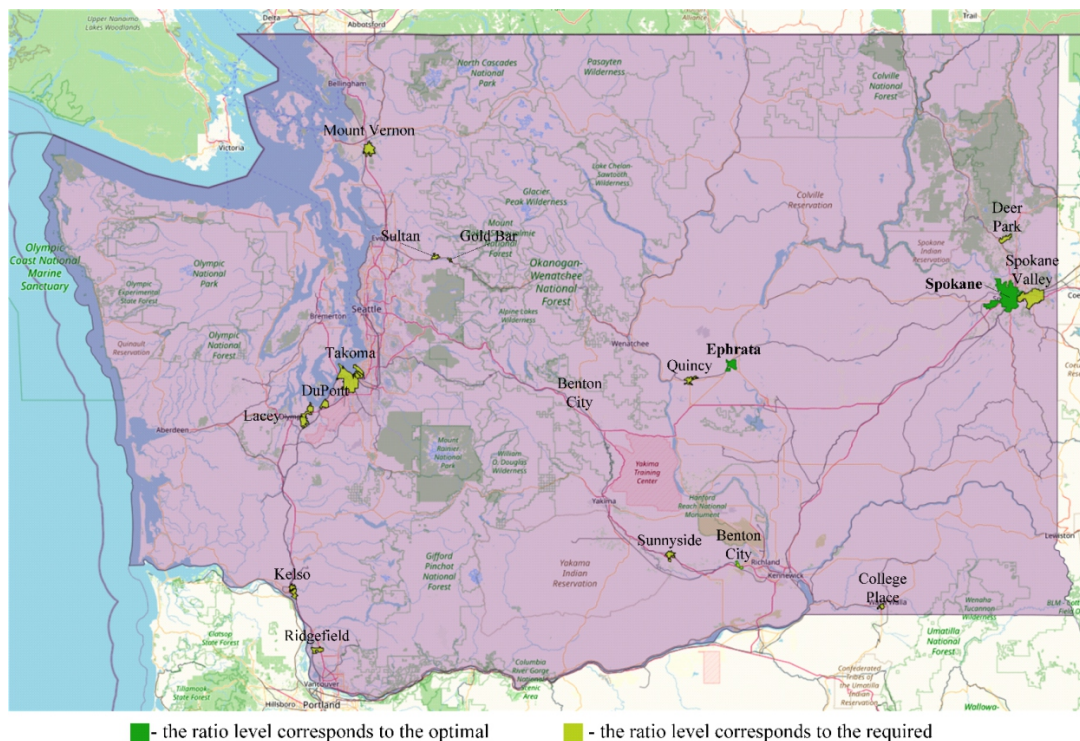■ - the ratio level corresponds to the optimal   ■ - the ratio level corresponds to the required

Fig. 3. Geoinformation location of ILs with the optimal and required ratio level in Washington State
(composed by the authors)

Rys. 3. Geoinformacja o lokalizacji IL o optymalnym i wymaganym poziomie wskaźnika w stanie Waszyngton

pose of such calculations was to test the hypothesis that disparities in the EV market may be found exclusively in large, medium-sized or small ILs. However, the calculations refuted this hypothesis since no relationship was found between the studied factors (the value of the coefficient is 0.001281) and therefore the market is developing chaotically.

An analytical review of indicators was performed through a comparison with the corresponding indicators in several countries of the world and cities with progressive EV markets. Figure 4 illustrates the obtained results in graphic format.
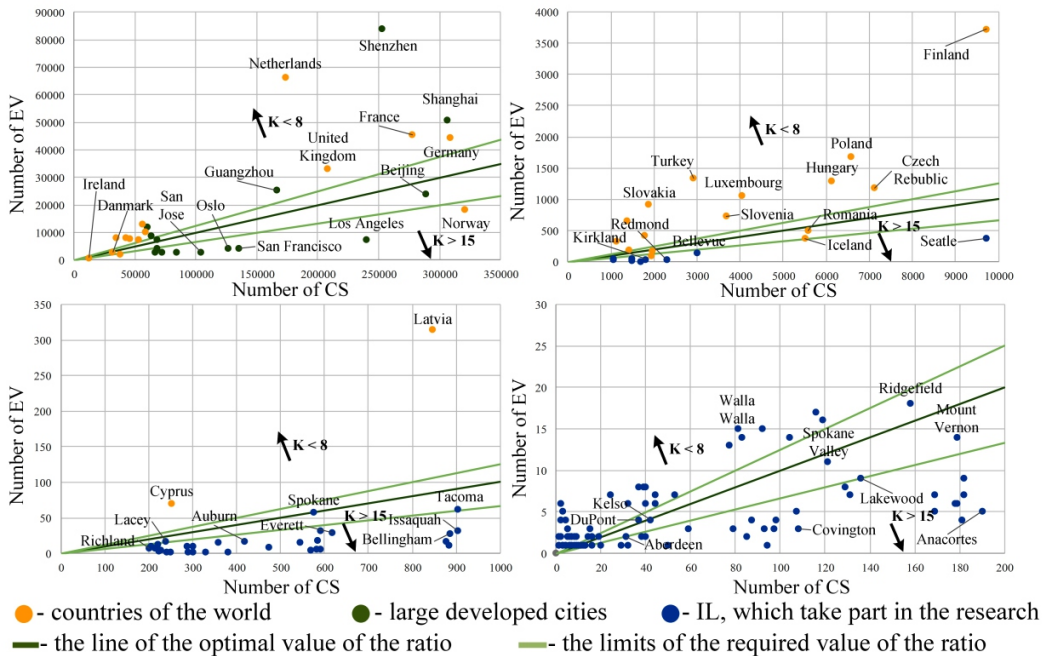

Fig. 4. An analytical view of the performance of the number of EVs and CSs from cities in the European regions, the largest cities of the world and ILs participating in the research
(composed by the authors taking into account (Hall 2020) and (European 2021))

Rys. 4. Analiza wyniku liczby pojazdów EV i CS w regionach europejskich oraz największych miast świata biorących udział w badaniu oraz ich IL

Analytical data presented in Figure 3 suggests that most European countries demonstrate infrastructural insufficiency. By contrast, the major cities of the world have an excess of CS infrastructure. This fact confirms disproportions in development, prevailing innovative attraction to business centres, strong links with urbanization and other globalization processes. American cities that took part in the research demonstrate an excess infrastructure. Cities with large EV numbers are more often characterized by infrastructural redundancy. An insignificant number of ILs and countries showed ratios within the calculated range of required and optimal ratio values.

2. **The coefficient of EV ownership characterizes the number of EV per 1 million population.** This indicator reflects the EV market saturation and the population's propensity to innovate and apply advanced environmental solutions; it is determined by the formula:

$$\text{K}_{EV\,per\,1M} = \frac{N_{EV} * 1,000,000}{N_{Pop}}$$

where:

$\text{K}_{EV\,per1M}$ – EV and CS ratio, where $\text{K}_{EV\,per1M} > 0$,

N_{EV} – designates the number of EVs registered in the territory of the IL in units, where $N_{EV} \in Z$ and $N_{EV} > 0$;

N_{Pop} – the number of CSs located in the territory of the IL in units, where $N_{Pop} \in Z$ and $N_{Pop} > 0$.

The indicator is used by scientific institutions to assess the EV market saturation and determine the level of public demand (Hall 2020; Hall and Lutsey 2020; Slowik 2019) and others. On the condition that the balance in the EV market is achieved, which can be identified by calculating the EV and CS quantity ratios, the local authorities should create conditions for increasing the indicator. The latter will evidence of the development of an environmentally friendly private transport system.

According to the method of calculating the EV ownership coefficient, its feasible values may appear within the range (0;∞), while values greater than 1 million would mean that each resident owns more than 1 electric car. However, in modern conditions of EV market development, such values are difficult to achieve, especially for large cities. In future though, as internal combustion engines will be completely abandoned by automobile manufacturers and transitions are being made to exclusive EV use, this may become feasible.

The results of calculating values of the EV ownership coefficient for the selected ILs in Washington State are given in Table 4.

The comparatively small town of Langley demonstrated the highest indicator value with a population of 1,140 people and 79 EVs. Cities with a coefficient value higher than average are presented predominantly by small ILs with up to 40,000 population; however, among them there are also larger ILs, such as Bellevue and Kirkland. The representative of ILs that show values below the average level consist of 92 ILs and is varied in terms of ILs size (this representative group includes both small and large ILs, such as Seattle, Vancouver, Spokane and Tacoma).

In order to conduct an in-depth analysis, we compared the indicator values obtained at this stage of the analysis with the values that are considered typical for other large ILs in the USA (Fig. 5) (Nicholas 2019).

It is apparent from the diagram that there is no relationship between the city size and the number of EVs, there exists no relationship between the EV population ratio and the factors involved in calculating the ratio. As a conclusion, the relevant data indicate that the statement claiming that technological advancement is only available in large cities is incorrect, neither is the assumption regarding technology being attached to urbanization, etc.

Table 4. Characteristics of the studied set of ILs by EV ownership coefficient values

Tabela 4. Charakterystyka badanego zbioru IL według wartości współczynników własności EV

| Indicator value	Name of IL/ /number of IL in the sample	Indicator value/ /average indicator value	Population of the IL [people]
Maximum	Langley	69,298	1,140
Minimal	Connell	180	5,545
Average value	X	10,371	34,787
The number of IL is above average	39	25,056	1,637,261
The number of IL is below average	92	4,146	2,850,266
The largest in terms of population IL	Seattle city	12,893	753,675
The smallest in terms of population IL	Skykomish	9,090	220

Composed by the authors.
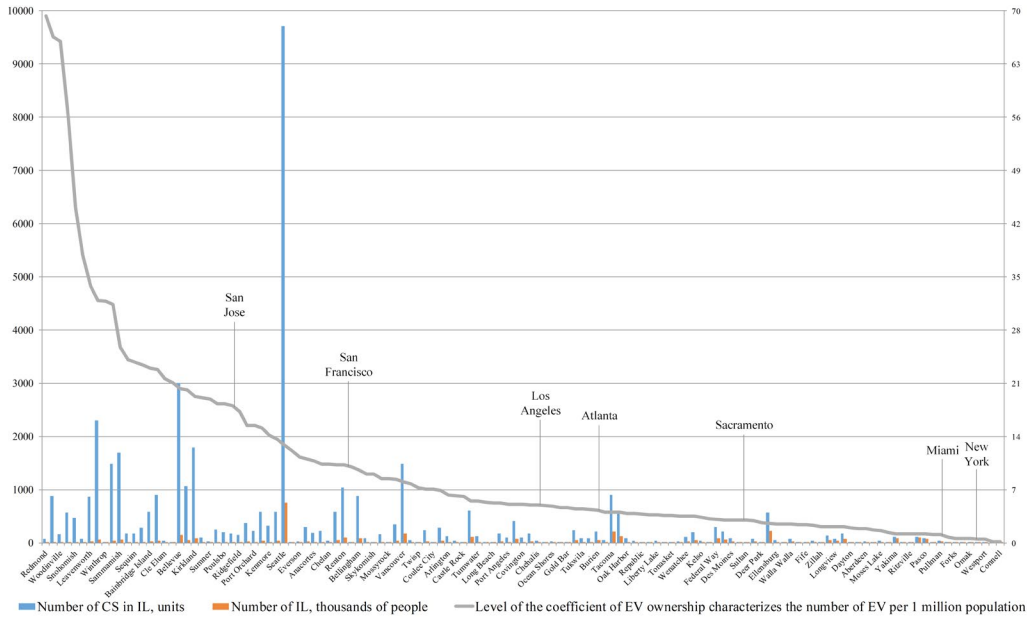
Fig. 5. Analytical characteristics of the EV ownership coefficient (composed by the authors)

Rys. 5. Charakterystyki analityczne współczynnika własności pojazdów elektrycznych EV

In order to achieve a stable increasing trend for the value of the indicator, local authorities should use a wholistic system of tools. Such tools that encourage the public to buy a car, in addition to direct measures to stimulate EV sales, may include additional compensation for the purchased cost of EV, subject to their registration and operation in a particular city or territory.

3. **CS location density factor characterizes the number of CS per 1 km² of territory.** In practice, this indicator is rarely used to describe the EV and CS market, although the factor is widely used in geodetic sciences to assess the degree of accumulation of certain infrastructure in a particular area. The appropriate infrastructure for EV charging should be distributed densely enough to make its use convenient and accessible. The factor is calculated by the formula:

$$K_d = \frac{N_{CS}}{S_{IL}}$$

where:

K_d –   the CS location density factor, where $K_d > 0$,

N_{CS} –   represents the number of CSs located in the territory of the IL in units, where and $N_{CS} \in Z$ and $N_{CS} > 0$,

S_{IL} –   the area of the IL [km²], where $S_{IL} \in R$ and $S_{IL} > 0$.

The calculation results of the CS location density factor for the selected set of ILs in Washington State are presented in Table 5.

The calculations established the average density of CS locations for 129 selected ILs in Washington State, which constituted 1.26 on average, which means one CS is located on the area of 794 m². Thirty-seven ILs exceed the mean value for the studied IL set in 2.27 times, while for ninety-two ILs, the factor is 49.2% lower than the mean factor value. The situation in two ILs, Skykomish and Camas, where the CS location density factor demonstrated extreme values, deserves more detailed attention.

Conducting such a study, primarily by determining the EV users' opinions through representatives and surveys, would assemble a realistic psycho-emotional picture showing if the local population is satisfied with EVs, the available service and if they think that the number of CSs is sufficient in the area.

TABLE 5. Characteristics of the set of IL by the value of the CS location density factor

TABELA 5. Charakterystyka zbioru IL przez wartość skupień czynników gęstości lokalizacji CS

Indicator value	Name of IL/number of IL in the sample	Indicator value/mean indicator value
Maximum	Skykomish	12.90
Minimal	Camas	0.07
Mean	X	1.26
The number of ILs that are above average	37	2.86
The number of ILs that are below average	92	0.62

Composed by the authors.

Thus, the current study provided a system of three indicators which allow real-time monitoring of the intensity and prospective trends in EV and CS markets in a particular area. The system of equations is as follows:

$$
\begin{cases} 8 < K_{\text{ÄV}/CS} < 15 \\ K_{\text{ÄV per 1M}} \rightarrow \max \quad (1) \\ \quad K_d \rightarrow \max \end{cases} \text{or} \begin{cases} 8 < \dfrac{N_{EV}}{N_{CS}} < 15 \\ \dfrac{N_{EV}*1000\,000}{N_{Pop}} \rightarrow \max \quad (2) \\ \dfrac{N_{CS}}{S_{IL}} \rightarrow \max \end{cases}
$$

Analysing the mathematical model (2), we concluded that the values of the IL's area (S_{IL}) and the IL's population (N_{Pop}) do not seem to be dynamically changing, while the values of EV number (N_{EV}) and CS number (N_{CS}) are changing dynamically. Given the above, only the values of EV (N_{EV}) and CS (N_{CS}) shall be considered in this study.

Relying on the data obtained through the system of indicators, regional authorities will be able to make rational management decisions regarding the advisability of stimulating or restraining measures for the population, car manufacturers and businesses to activate the EV and CS market.

Case 5 was performed using the Science Hunter analytical service (Science Hunter 2021). With the help of the appropriate service, the method of k-means and Euclidean metrics, we clustered the data obtained by calculating the three indicators for 129 ILs in Washington State, USA. Due to a special feature of the k-means method, several clustering iterations were performed, and the nearest valid variant was selected applying the mathematical apparatus, which included sum of the squared errors index, Trace index, Dunn index, Davies-Bouldin index, Calinski-Harabasz index, PBM index. The most optimal clustering is indicated below and includes:

$$
\begin{cases} \text{Sum of the squared errors index®min} \\ \text{Trace index®min} \\ \text{Dunn index®max} \\ \text{Davies-Bouldin index®min} \\ \text{Calinski-Harabasz index®max} \\ \text{PBM index®max} \end{cases} \quad (3)
$$

The number of clusters was substantiated according to the Strages rule. The obtained clustering results which are the most optimal in view of the calculated indices are summarised in Table 6.

According to the calculation results, 129 ILs were divided among eight homogeneous clusters according to the selected EV and CS market characteristics. Such an approach provides a set of eight clusters with the spatial arrangement of the elements as shown in Figure 6. As is

TABLE 6. Complex characteristics of the selected clusters

TABELA 6. Kompleksowa charakterystyka wybranych klastrów

Number of clusters	Sum of the squared errors index	Trace index	Dunn index	Davies--Bouldin index	Calinski--Harabasz index	PBM index
8	–0.571	5127.750	0.144	6.211	30.606	6163.115

Composed by the authors taking into account (Science Hunter 2021).

obvious from Figure 6, Clusters 7 and 8 (represented in the figure by green and pink dots, respectively) contain the largest number of elements, which are placed close to each other. Thus, we do not anticipate any significant differences between their characteristics. Clusters 3, 5 and 6 (represented by blue, purple and gray dots, respectively) are located more remotely from each other, consequently, the difference between them is expected to be more significant. Clusters 1, 2 and 4 (represented by orange, yellow and red colours, respectively) are placed at the greatest distance; therefore, the most significant difference in characteristics is expected.
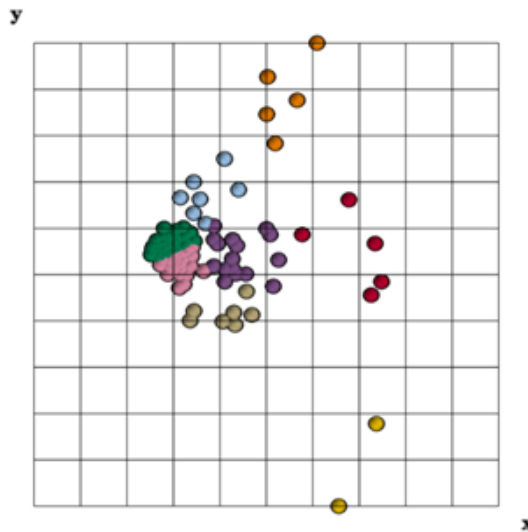

Fig. 6. Spatial locations of clusters (composed by the authors taking into account (Science Hunter 2021))

Rys. 6. Rozmieszczenie przestrzenne klastrów

Additionally, to evaluate the results of clustering, the number of participants in each cluster and the mean values of the three coefficients were determined, which were incorporated into the evaluation system in the next stage. The corresponding results are presented in Table 7 and in Figure 7 with normalized values of the corresponding columns.

TABLE 7. Characteristics of selected clusters

TABELA 7. Charakterystyka wybranych klastrów

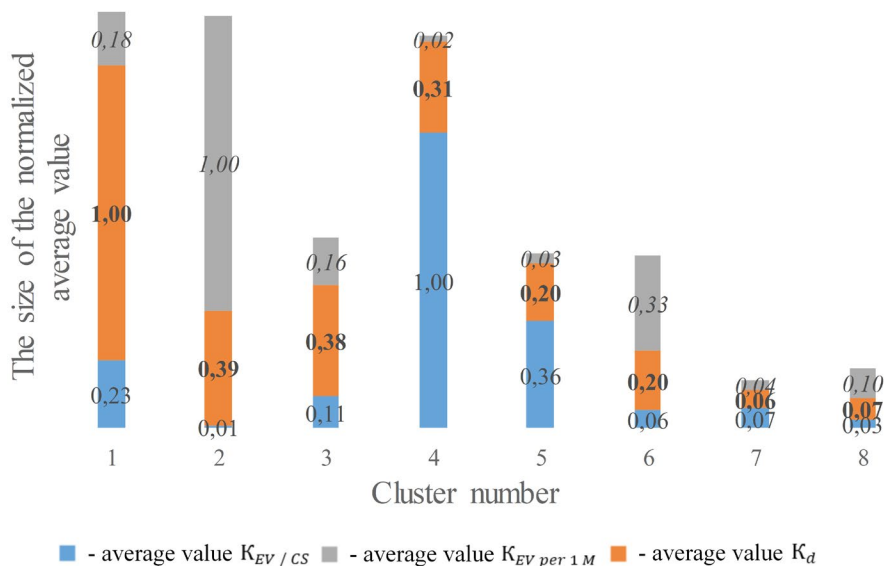| Cluster number	Number of ILs in the cluster	Mean value, $K_{EV/CS}$	Mean value, $K_{EV\ per\ 1M}$	Mean value, K_d
1	5	66.37	60 382.51	2.12
2	2	3.21	23 520.32	11.74
3	16	30.65	22 990.56	1.86
4	5	285.85	18 813.05	0.21
5	7	103.48	12 135.98	0.36
6	7	17.44	12 089.93	3.83
7	47	19.01	3 786.89	0.44
8	40	8.56	4 484.76	1.20

Composed by the authors.

Fig. 7. Graphical display of normalized mean values of the studied coefficients in different clusters to estimate the difference (composed by the authors)

Rys. 7. Graficzne przedstawienie znormalizowanych średnich wartości badanych współczynników w różnych skupieniach w celu oszacowania różnicy

Eight clusters were obtained, each including from 2 to 47 ILs. The clusters that contain fewer elements were investigated first. Each cluster possesses the following characteristics of the EV market infrastructure depending on the mean values of the indicators selected for the study:

- *Cluster 1* includes 5 ILs, which are characterized by a high rate of EV ownership among the population, with above-average density of the CS territorial location and a low level of infrastructure provision for existing EVs by stationary CSs;
- *Cluster 2* includes 2 ILs, which are characterized by high EV ownership among the population at the highest density of the territorial location of the CSs and a very high level of infrastructure support of existing EVs with stationary CSs;
- *Cluster 3* includes 16 ILs, which are characterized by high EV ownership at above average density of the territorial location of the CSs and low (value above the optimal but less than average levels) infrastructure of stationary CSs to support the existing EVs;
- *Cluster 4* includes 5 ILs, which are characterized by a high EV ownership level among the population at an ultra-low level of density of the CS territorial distribution and ultra-low (minimum possible indicator value) infrastructure of stationary CSs to support the existing EVs;
- *Cluster 5* includes 7 ILs, which are characterized by an average EV ownership level among the population at an ultra-low level of density of CS territorial location and ultra-low level of infrastructure support for existing EVs provided by stationary CSs;
- *Cluster 6* includes 7 ILs, which are characterized by an average EV ownership level among the population at an above-average level of density of the CS territorial distribution and close to the average (higher than optimal and less than average) level of infrastructure support for existing EVs by stationary CSs;
- *Cluster 7* includes 47 ILs, which are characterized by an ultra-low EV ownership level among the population at an ultra-low level of density of the CS territorial distribution and close to the average (higher than optimal and lower than average) level of infrastructure of stationary CSs to support existing EVs;
- *Cluster 8* includes 40 ILs, which are characterized by an ultra-low EV ownership level among the population at an average level of density of the territorial location of the CSs and close to the optimal infrastructure of stationary CSs to support existing EVs.

Each of the selected clusters requires an individual strategy to balance the EV market in the future and to bring market parameters to the requirements stated in the mathematical model (1). The findings of this study suggest that a wide range of tools and leverages can be used to correct the situation, including all types of financial incentives, advertising, mechanisms of environmental pressure, territorial preferences, etc. The study presents basic recommendations for balancing the EV market within the selected clusters for Washington State (Table 8).

The orientation of IL management towards the proposed recommendations should guarantee the rational regulation of the EV market, from which all market participants will benefit increasingly.

TABLE 8. Basic recommendations for balancing the EV market within the selected clusters
for Washington State, USA

TABELA 8. Podstawowe rekomendacje dotyczące bilansowania rynku EV w wybranych klastrach
dla stanu Waszyngton, USA

Cluster number	Recommendations for achieving balanced conditions and efficient EV market
1, 4, 5	Developing and implementing measures by the IL authorities aimed at motivating CS owners to increase EV ownership on the territory of the IL while simultaneously applying explanatory measures for the population regarding the need to restrain the desire to purchase and use new EVs in order to avoid inconvenience and problems during use. Restrictive measures should be in place until the EV market is balanced. From the moment when balanced conditions for characteristics of EV market functioning are achieved, these specified measures should be of a preventive nature.
3, 6	Developing and implementing measures by IL management to motivate CS owners to increase their number significantly on the territory of the IL while controlling the dynamics of increasing the EV number. In the case of significant deviations from the limit values of the indicators proposed for monitoring, it is expedient to introduce stricter regulatory measures.
2	Developing and implementing measures by the IL management to maintain the achieved level of EV market balance and maintaining the microclimate that has been created in the IL through the EV/CS ratio. Monitoring the values of the indicators studied here will prevent negative instances that may unbalance the EV market.
7	Developing and implementing measures by the IL authorities to activate the EV market, simultaneously motivating CS owners to increase their number in the ILs and promoting the expediency and public purchasing of EVs among the population. Local authorities should monitor the values of the proposed coefficients in order to prevent imbalance in the EV market functioning.
8	Developing and implementing measures by IL management to promote environmental safety and economic efficiency of purchasing and operating EVs by the population of the IL. It is necessary to introduce a temporary ban on designing and constructing new CSs on the territory of the IL, since there will be no demand for their services until the number of EVs and existing CSs is balanced.

Composed by the authors.

Conclusion

This paper has argued that an effective EV market development should not happen in a chaotic way. To enhance and further develop the market, the article recommends following clear rules for the quantitative balancing EVs and CSs, in addition to considering purely technical and technological aspects of EV building and CS construction. While studying the example of the EV market in Washington State (USA), the authors have offered unified approaches to balancing the EV market, while market development analysis has identified a model by which development reaches its optimal values and enabled a cluster analysis of ILs within the state based on indicators describing EV and CS properties. The study has revealed that the EV market in the state is not homogeneous and is developing erratically. To achieve the effectiveness of market development, various economic, social and other tools may be applied, while each cluster and

IL requires an individual approach. The results obtained during the study may be of use while monitoring trends in the EV market of other US states and other world regions, which will create favourable conditions for the natural and efficient transition of road users to use electric transport with the maximum positive impact on the environment. Further research in this field would be of help in motivating government agencies in the world to implement incentives to create balanced infrastructure support for the existing EV market while taking into account architectural, marketing and social aspects along with purely financial factors.

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Zarządzanie rynkiem nowoczesnych pojazdów elektrycznych

Streszczenie

Artykuł udowadnia, że trendem rozwoju nowoczesnego transportu na świecie jest maksymalizacja poziomu zapewnienia osobistej użyteczności pojazdów elektrycznych. Mechanizm ten częściowo rozwiązałby również problemy środowiskowe ludzkości. Aby zrealizować ten pomysł, niektórzy światowi producenci samochodów ogłosili decyzję o całkowitym przejściu produkcji na pojazdy elektryczne. Ale dla efektywnego funkcjonowania rynku pojazdów elektrycznych konieczne jest stworzenie odpowiedniej infrastruktury.

Istnieje pozytywna tendencja rocznego wzrostu sieci stacji ładowania w krajach rozwiniętych, która charakteryzuje rynek stacji ładowania jako dynamiczny i obiecujący, ale w większości chaotyczny i niezrównoważony na poziomie regionalnym.

Główna hipoteza postawiona w badaniach dotyczy niezależności pomiędzy poziomem rozwoju rynku pojazdów elektrycznych a sieciami stacji ładowania. Przedmiotem badania jest waszyngtoński (USA) rynek pojazdów elektrycznych, ponieważ jest to segment rynku o najwyższych cechach rozwoju.

W celu sprawdzenia hipotezy autorzy przeprowadzili wieloczynnikową analizę lokalnego rynku pojazdów elektrycznych oraz istniejącej infrastruktury ładowania. Przeprowadzono kompleksową analizę rynku pojazdów elektrycznych oraz sieci stacji ładowania w Waszyngtonie (USA) i odpowiednio określono cechy rynku: stopień rozproszenia pojazdów elektrycznych w regionach; poziom pokrycia i koncentracji sieci stacji ładowania; stosunek pojazdów elektrycznych do stacji ładowania.

Autorzy zidentyfikowali trend na poziomie państwa związany z innowacjami dotyczącymi pojazdów elektrycznych. Dokonano klasteryzacji i opracowano rekomendacje dotyczące poziomu rozwoju rynku pojazdów elektrycznych, które ma na celu zrównoważenie i rozwój całego rynku pojazdów elektrycznych i połączonej infrastruktury.

Słowa kluczowe: pojazd elektryczny, USA, lokalizacja, rynek pojazdów elektrycznych, stacja ładowania