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SUITABLE LAW-BASED LOCATION SELECTION OF HIGH-POWER ELECTRIC VEHICLES CHARGING STATIONS ON THE TEN-T CORE NETWORK FOR SUSTAINABILITY: A CASE OF POLAND

Maciej MAZUR[1], Jacek DYBAŁA[2], Aldona KLUCZEK[3]

[1] *Polish Alternative Fuels Association*

[2] *Warsaw University of Technology, Faculty of Automotive and Construction Machinery Engineering, Warsaw, Poland*

[3] *Warsaw University of Technology, Faculty of Mechanical and Industrial Engineering, Warsaw, Poland*

Abstract:

With the upcoming implementation of the amendment to Regulation (EU) 2019/631 of the European Parliament and of the Council, from 2035 there will be a ban on the registration of new vehicles with internal combustion engines (ICE) in the Member States of the European Union (EU). Consequently, changes in the transportation sector, resulting from the increasing use of electric vehicles, appear to be inevitable. According to the adopted legal acts, the European Union Member States will be obliged to develop, among others, a charging infrastructure and access to public charging stations for electric vehicles. As a result, there will be a need to ensure a significant increase in the power and the number of charging stations and to determine their appropriate location. The article presents the challenges faced by charging station operators and difficulties related to the further development of electric vehicle charging infrastructure in Poland. The still poorly developed public charging infrastructure for electric vehicles, especially in service areas located along the main communication routes, remains the main obstacle to the development of electromobility. In the context of legal, financial, technological, and organizational challenges, the problem of the proper distribution of electric vehicle charging stations along the main communication routes is therefore of particular importance. The aim of the article is to present a new, proprietary method for determining the location of electric vehicle charging stations in Poland within the Trans-European Transport Network (TEN-T), which considers objective location factors: adherence to AFIR requirements, the specificity of the Polish power system and existing parking infrastructure. As a result of using the developed method, a list of 188 recommended locations for the construction of electric vehicle charging stations in Poland along the Trans-European Transport Network (TEN-T) was created. It has been shown in this way that the use of the presented method enables the suitable determination of the location of electric vehicle charging stations along transport routes, considering legal, financial, and technological requirements, which will significantly facilitate the operation of zero-emission transport.

Keywords: *AFIR, electric vehicles charging stations, law-based method, TEN-T core network*

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Contact:
1) maciej.mazur@pspa.com.pl [https://orcid.org/0009-0003-1370-6758]; 2) jacek.dybala@pw.edu.pl [https://orcid.org/0000-0002-0721-1105]; 3) aldona.kluczek@pw.edu.pl [https://orcid.org/0000-0002-0156-4604] – corresponding author

1. Introduction

The transport sector, particularly road transport, plays a pivotal role in addressing environmental challenges and meeting Sustainable Development Goals (SDGs) (Pietrzak & Pietrzak, 2020; Holzwarth, 2015), especially Goal 9 and Goal 11, as emphasized by (Holzwarth, 2015). This perspective is further expanded upon by (Dominika & Stankowska, 2021). To combat climate change, the European Union (EU) has set ambitious targets to reduce greenhouse gas emissions emissions by 90 % by 2050 vs. 1990, including a ban on new internal combustion engine (ICE) vehicles from 2035 (European Commission, 2022). The European Parliament and the Council of the EU have agreed to amend Regulation 2019/631 (Fit for 55, 2022), which will mandate the sale of only zero-emission cars and vans in the new vehicle segment throughout the EU from 2035. However, a significant obstacle to the development of electromobility, especially in Poland, remains the underdeveloped public infrastructure for charging electric vehicles (EVs) (PSPA, 2022). The forthcoming adoption of AFIR regulations (Fit for 55, 2022) will require Member States to develop a network of public high-power charging stations. Poland must notably expand its charging station network along the Trans-European Transport Network (TEN-T) . Significantly, Poland boasts the third-largest coverage of the Trans-European Transport Network (TEN-T)[1] network within the European Union, spanning 7,501 kilometers, representing 10.6% of the entire network length (see Fig. 1) (European Commission, 2023).

AFIR (Regulation for the Deployment of Alternative Fuels Infrastructure – AFIR) replaces Directive 2014/94/EU of the European Parliament and of the Council, taking effect from April 13, 2024, as part of the "Fit for 55" package (European Parliament, 2023). In the area of infrastructure, AFIR imposes obligations on electric light vehicles (LDVs), requiring charging intervals of 60 km along the TEN-T core network with a total capacity of at least 400 kW by 2025, increasing to 600 kW by 2027. Similar requirements apply to the comprehensive TEN-T network (with milestones set for 2027, 2030, and 2035). For electric heavy-duty vehicles, the regulation's objectives include the requirement to cover at least 15% of the length of the TEN-T network with charging zones, each with a capacity of at least 1.4 MW, by the end of 2025, with a maximum spacing of 120 km. By 2027 and 2030, these requirements for the TEN-T network will increase to 50%, and the capacity of an individual zone must be at least 2.8 MW.

By 2030, 100% of the TEN-T network must be electrified, with core network zones, having a minimum capacity of 3.6 MW, spaced at least 60 km apart.

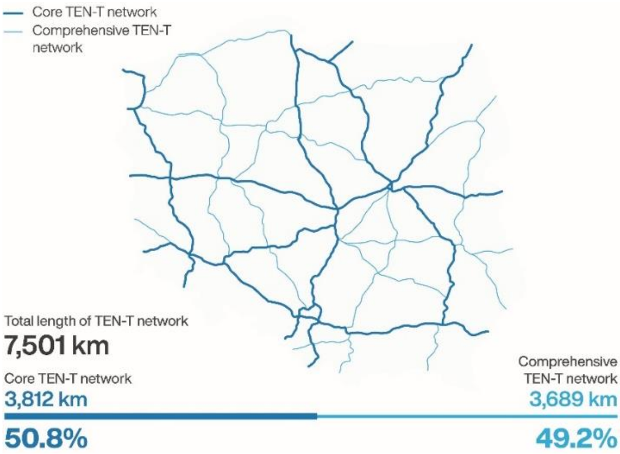

Fig. 1. Comprehensive and core TEN-T network in Poland (Source: Own elaboration based on the data of General Directorate for National Roads and Motorways - GDDKiA)

[1] The TEN-T serves as a coordinating instrument to ensure the coherence and complementarity of infrastructure investments, as well as the smooth flow of people and goods

The need to create an extensive network of electric vehicle charging stations is a significant barrier to the development of electrified road transport in Poland (Chmielewski et al., 2023). Considering the projections for the growth of the Polish BEV and PHEV fleet as indicated by (PSPA, 2022), there is a need to boost the capacity of charging stations in Poland. By 2025, the capacity should increase to 435.8 MW, escalating to 1383.5 MW by 2030, and further to 2613.1 MW in 2035. This necessitates a substantial 29-fold increase in the installed capacity of public infrastructure by 2035. Future plans call for a total capacity of 723 MW, encompassing 252 charging stations for Light-Duty Vehicles (LDVs) and 202 for Heavy-Duty Vehicles (HDVs). Fulfilling the AFIR requirements presents a substantial challenge (Table 1).

The expansion of the EV fleet and charging infrastructure development are interdependent processes. The perceived lack of practical guidelines considering objective location factors, including the specificity of the power system and existing parking infrastructure, hinders the development of EV charging infrastructure, and the designation of appropriate locations for charging stations becomes a serious challenge. To meet this challenge, decision-makers must select suitable locations for EV charging stations while considering complex legal, financial, technological, and organizational aspects. While AFIR regulations set goals for EV fleets, it does not automatically offer a recipe for rational placement of EV charging stations in the transportation environment. Despite the publication of several scientific papers on the location of EV charging stations (Frade et al., 2011; Tian et al., 2018; Xiao et al., 2020; Zhao et al., 2020), which mostly use optimization models, lacks a noteworthy method for selecting suitable charging station locations according to legal, financial, technological and organizational aspects. There is no doubt that there is a significant research gap in this area. Consultations with a wide range of stakeholders, including current service area leaseholders, distribution network operators, and charging station operators, have revealed that the method for determining the location of EV charging stations should consider not only the distance between stations but also other factors. These include assessing functionality, notification methods, and cost and time criteria related to the supply of energy from the power system. The goal of the study is to develop a structured approach for selecting the location of EV charging infrastructure for both light and heavy transport in Poland, that aligns with the AFIR regulations within the European Union. Therefore, this article presents a new, original method for determining the location of charging infrastructure for electric Light-Duty Vehicles (eLDVs) and electric Heavy-Duty Vehicles (eHDVs) along roads belonging to the core Trans-European Transport Network (TEN-T), which considers objective location factors and takes into account not only AFIR requirements, but also the specificity of the power system and existing parking infrastructure.

The developed five-stage approach to identifying suitable EV charging station locations as potential locations assumed existing car parks (Rest and Service Areas - RSAs) located along the TEN-T transport network. From the customer's point of view, a good location of a public charging station should be characterized primarily by good signage and easy access for owners of electric vehicles, as well as ensuring the possibility of pleasant use of time for drivers waiting for the charging process to be completed. For these reasons, locating charging stations in RSAs seems to be a very interesting solution. When assessing each location, the following factors were considered: the time and cost of implementing the investment consisting in creating a charging station for electric vehicles, the amount of the fee for connecting the charging station to the power system, the category of the parking lot and the number of available parking spaces adapted for LDVs and HDVs.

Table 1. Total capacity and theoretical number of locations to be electrified (by LDVs and HDVs) on the TEN-T core and comprehensive network (Source: Own elaboration)

	2025	**2027**	**2030**	**2035**
AFIR	LDV: **128**	LDV: **190**	LDV: **252**	LDV: **252**
	HDV: **20**	HDV: **64**	HDV: **202**	HDV: **202**
	79 MW	**187 MW**	**686 MW**	**723 MW**
	LDV: 51 MW	LDV: 95 MW	LDV: 114 MW	LDV: 151 MW
	HDV: 28 MW	HDV: 92 MW	HDV: 572 MW	HDV: 572 MW

A weighted points system was used to assess the location of each charging station. Seven factors influencing the rating of each location were assigned specific points, and appropriate weights were assigned based on their importance in the final rating of the location.
The proposed method facilitated the implementation of the task to determine the suitable locations of charging infrastructure for both eLDVs and eHDVs along roads within the TEN-T core network, in line with AFIR requirements. This pioneering solution made it possible to identify, in financial, technical and time terms, the investments necessary for the development of zero-emission transport in Poland and required to meet the AFIR standards.

2. Literature review

A growing body of research (Brdulak et al., 2020; Ghosh, 2021) has focused on developing charging infrastructure to overcome the major challenge of limited EV range. Notable models include theoretical optimization models for high-power charging (HPC) stations and ad-hoc models for highway and expressway deployment (Jochem et al., 2019). Theoretical models, such as the one presented by (Church & Velle, 1974), aim to minimize the number of alternative fuel stations along motorway systems. Some of these models, like the one by (Hodgson, 1990), analyze vehicle flows, while (Upchurch & Kuby, 2010) introduce a location model that considers several refueling stops during long-distance journeys. However, computational limitations make them impractical for large networks. Attempts to redefine EV charging station deployment have been made, considering travelers' and the electricity grid's perspectives (Csiszár et al., 2020). These approaches consider power grid capacity and travel patterns (Gong et al., 2016) and involve both nodal or point-based approaches (Gong et al., 2016; Hodgson, 1990) as well as an origin-destination matrix (Jochem et al., 2019). Models like those by (Shirmohammadli & Vallée, 2017) focus on the potential of motorway segments for installing fast charging stations. A similar approach to the previous one was presented in (Napoli et al., 2020). In contrast, an approach, presented by (Yi & Bauer, 2016) uses data from both the EV flow and the road network to determine the appropriate sizing and location of the charging infrastructure along the motorway network. The developed model allows for simultaneous determination of the location of fuel stations and the number of charging points to be located within them. Various studies have explored sustainable EV charging station infrastructure, employing a range of optimization methods. These methods consider economic, social, and environmental factors. For instance, (Zhou et al., 2022) used genetic algorithms to optimize charging station placement from economic, social, and environmental perspective. Some approaches incorporate Multi-Criteria Decision Analysis (MCDA) to evaluate optimal routes for sustainable transport. Decision support systems, including Geographic Information System (GIS) techniques and MCDM, have been utilized to identify suitable charging station locations (Guler & Yomralioglu, 2020). (Abdel-Basset et al., 2023) developed a methodology using DEMATEL and COPRAS methods to evaluate EV charging station locations. The issue of managing uncertainty in the selection of electric vehicle charging stations was addressed effectively by using a comprehensive fuzzy decision matrix, constructed based on the fuzzy weighted interaction geometric (PFWIG) (Ju et al., 2019). In a similar vein, a novel decision-making analysis method, the grey relational projection method, was developed to handle scenarios where attribute weights are unknown (Zhang et al., 2013). In the next study, (Wang et al., 2013) respected a programming method for multi-criteria decision-making that relies on intuitionistic trapezoidal fuzzy numbers when handling incomplete and uncertain information.
Consequently, other researchers (Efthymiou et al., 2017) tackled an optimization problem using linear programming, multi-objective optimization, and genetic algorithms, focusing on the deployment of public EV charger networks. This exploration was prompted by the anticipation of the deployment of public electric vehicle charger networks. Many instances necessitate the evaluation of high-power charging infrastructure for electric vehicles are based on decision support considering interests of all the stakeholders involved in the infrastructure (Danese et al., 2022), and using linguistic variables instead of crisp values (Pamucar et al., 2021).
Although these methods consider various sustainability aspects, none of them incorporates a law-based approach for location selection, posing a gap in the existing literature. Additionally, the available literature does not yet consider the practical approach of

experts to selecting the location of electric vehicle charging stations. The literature presented in table 2 mainly focuses on sustainability aspects of selecting EV charging stations. The absence of a legal approach in current scientific methods underscores the need for a universal, data-driven, and legally compliant approach, as proposed by the authors.

In summary, this literature review presents a number of approaches to address the challenges associated with selecting optimal EV charging station locations, setting the stage for our study's unique contribution to filling the observed research gap. Because although existing literature offers various methods for selecting the location of EV charging stations based on economic, environmental, and social perspectives, these approaches lack a legal aspect. To fill this gap, our study introduces a law-based approach to the selection of charging station locations, which additionally considers the knowledge of subject experts, thus ensuring the universality, simplicity, and compliance of the developed method with EU regulations.

Table 2. (No)Sustainability aspects in the selection of electric vehicle charging stations (Source: Own elaboration)

References	Country	Research field	Methods/approaches used	Sustainability
(Guo & Zhao, 2015)	China	selection of electric vehicle charging station considering criteria of sustainability	MDCA+ fuzzyTOPSIS	yes
(Wu et al., 2017)	China	residential areas	fuzzyVIKOR +	yes
(Sadeghi-Barzani et al., 2014)	No indicated	optimization approach for optimal placing and sizing of the fast-charging stations considering economic factors of energy	Mixed-Integer Non-Linear (MINLP) optimization approach	no
(Guler & Yomralioglu, 2020)	Turkey	urban areas	Geographic Information System (GIS) + AHP + Fuzzy AHP + TOPSIS	yes
(Ju et al., 2019)	China	electric vehicle charge selection site selection considering conflicting criteria	PFNs + PFWIG +FAHP	yes
(Pamucar et al., 2021)	United States	selection and ranking of a group of BEVs	MCDM based on FUCOM-F + MARCOS	yes
(Sałabun & Karczmarczyk, 2018)	Poland	selection of a BEV for sustainable city transport	COMET	no
(Ziemba, 2021)	Poland	analyse the A–C segments of the Polish electric vehicle market	NEAT F-PROMETHEE, fuzzy TOPSIS and fuzzy SAW	no
(Wu et al., 2016)	China	development for optimal site selection of Electric Vehicle Charging Stations	Cloud Model and the PROMETHEE Method https://www.mdpi.com/1996-1073/9/3/157	yes
(Zhou et al., 2022)	Ireland	optimal placement EVC stations in Irish 5 cities	Genetic algorithm	yes
(Abdel-Basset et al., 2023)	Egypt	identification of the most sustainable location for an EV charging station using sustainability assessment method	DEMATEL and COPRAS methods	partially

Legend: AHP – Analytical Hierarchy Process; FAHP - Fuzzy Analytic Hierarchy Process; COMET—Characteristic Objects METhod; COPRAS- Complex Proportional Assessment; DEMATEL- Decision-making Trial and Evaluation Laboratory; FUCOM-F- fuzzy Full Consistency Method; MARCOS- neutrosophic fuzzy Measurement Alternatives and Ranking according to the COmpromise Solution (MARCOS); TOPSIS- The Technique for Order Preference by Similarity to Ideal Solution, PROMETHEE- Preference Ranking Organization Method for Enrichment Evaluations; VIKOR—vIsekrzterijumska optimizacija i kompromisno resenje; PFN - picture fuzzy numbers; PFWIG - fuzzy weighted interaction geometric

3. Method for determining the location of EV charging stations

The authors method described in this section incorporating the AFIR criteria provides a model for the decision-making process as the part of the project entitled *"The project of optimal locations for charging infrastructure for light-duty and heavy-duty vehicles along roads in the TEN-T core network corridor, taking into account the requirements of the draft regulation of the European Parliament and of the Council on the development of alternative fuels infrastructure and repealing Directive 2014/94/EU of the European Parliament and of the Council (AFIR)".* The research was done between 24 August and 16 December 2022 by the Polish Alternative Fuels Association commissioned by the Ministry of Climate and Environment in Poland. The authors of this article were engaged to implement the project in cooperation with PSPA.

The developed expert approach defines a method not yet known in the available literature on the topic, and at the same time consistent with EU law. A five-step expert approach was illustrated in Fig. 2.

The individual stages of the developed approach are described as follows:

1st Stage: *Determining a list of potential locations for charging infrastructure for electric vehicles.*

To develop a relevant scenario for charging infrastructure deployment in the 2030 timeframe, an extensive list of potential locations was compiled, including Rest and Service Areas (RSAs) situated along the TEN-T core network. Data on the location of existing and future Service Areas was collected from the General Directorate of National Roads and Motorways (GDDKiA) to identify suitable locations for charging infrastructure development in line with AFIR guidelines. During this phase, consultations were conducted with various stakeholders involved in the development of charging infrastructure. It aimed at gauging potential industry interest in investing in the construction of fast charging stations at specific locations resulting from AFIR regulations. The distribution of locations received by GDDKiA and those indicated by market stakeholders was 522 vs. 293, respectively. The survey for developing a list of potential locations was conducted in October 2022 and involved a broad range of stakeholders from the e-mobility market, including representatives from the central administration, such as the Ministry of Climate and Environment and the Ministry of Infrastructure, as well as the General Directorate for National Roads and Motorways, the Polish Electricity Transmission and Distribution Association, and DSOs.

2nd Stage: *Location selection in accordance with AFIR requirements.*

In the second stage, the locations identified in the first stage were verified in accordance with AFIR requirements for both LDVs and HDVs. These requirements stipulated that the consecutive locations on the TEN-T network should not be more than 60 km apart by 2030 for both LDVs and HDVs. The list of locations was determined through consultations with current lessees, as well as business entities planning or operating charging infrastructure at the selected RSAs. The stakeholders were asked to identify locations where there is an interest in implementing infrastructure investments at the minimum level set out in AFIR regulations.

3rd Stage: *Selection of priority TEN-T sections (electrified first for HDV requirements).*

In this stage of the project, a selective process was conducted to determine which sections of the TEN-T network should be prioritized for electrification. The goal was to identify a limited number of locations of charging infrastructure for eHDV in 2025 and 2027. The selection was based on an analysis of a study commissioned by the European Automobile Manufacturers Association (ACEA) and conducted by Fraunhofer ISI (Plötz & Speth, 2021), which identified regular truck stops as optimal locations for charging infrastructure development. To identify these locations, data on the GPS coordinates of roughly 400,000 trucks across Europe was analyzed, revealing the highest density of activity on the E30 and E40 routes. In addition to this, in determining the optimal locations for charging infrastructure deployment, traffic volume along routes within the TEN-T network in Poland was considered. The General Directorate for National Roads and Motorways (GDDKiA) provided data in 2021 indicating that the E40 has the highest international road traffic volume in Poland, with an average of almost 38,000 motor vehicles per day. As a result, the routes included in the TEN-T core network were identified, where the development of charging infrastructure for eHDVs should be prioritized, while meeting the requirements set out in AFIR regulations for 2025 and 2027 about heavy transport (Fig. 3).

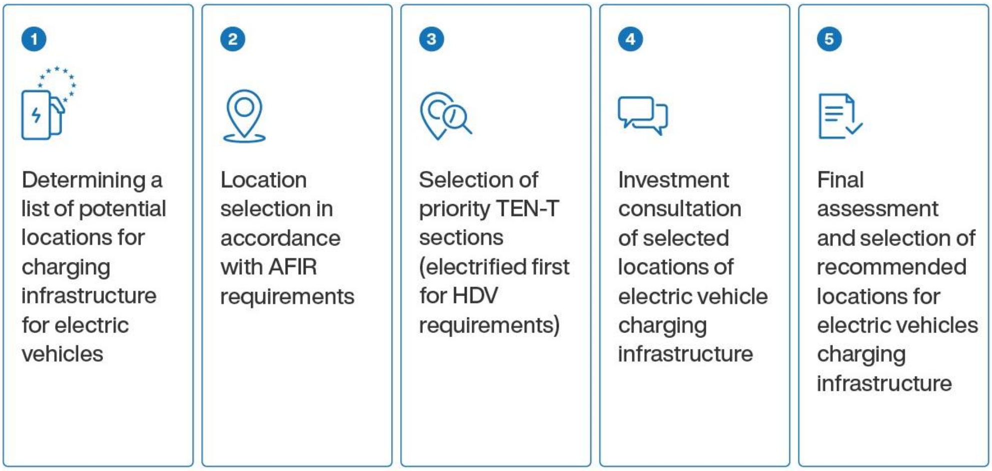

Fig. 2. The five-stage expert approach (Source: Own elaboration)

4th Stage: *Investment consultation of selected locations of electric vehicle charging infrastructure.*
This stage aimed to consult with specific Distribution System Operators (DSOs) regarding the required investments in the distribution network and to establish a preliminary timetable for carrying out the investments at the identified locations. The Polish Electricity Distribution and Transmission Association (PTPiREE) participated in the implementation of this stage. To obtain detailed information from the DSOs, a research questionnaire was developed, which covered the topics depicted in Fig. 4.

5th Stage: *Final assessment and selection of recommended locations for electric vehicle charging infrastructure.*
As part of this stage, a final list of recommended locations was determined through an evaluation process. The location selection was based on various criteria such as functionality, submission mode, cost, and time required for providing power from the distribution network.

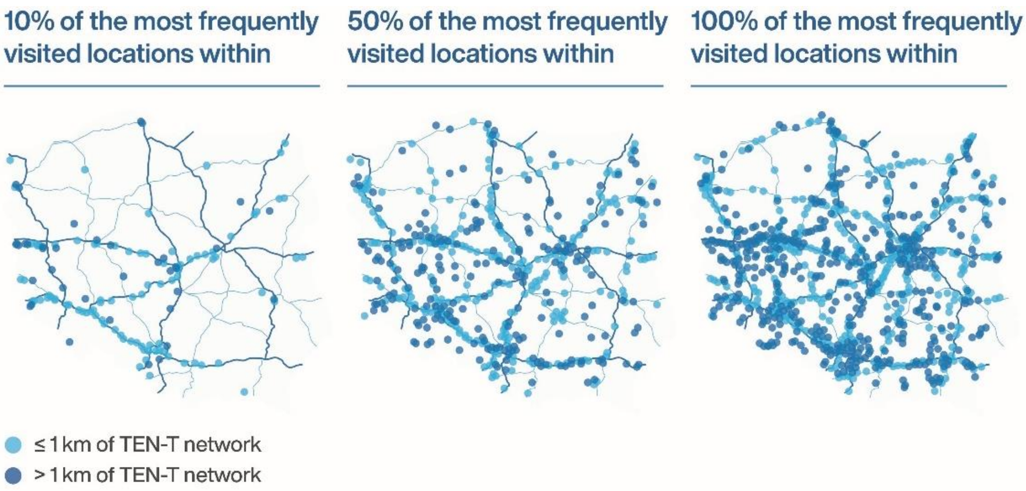

Fig. 3. Routes that are part of the TEN-T network, where the development of charging infrastructure for eHDVs should take place in the first place (Source: Own elaboration)

To evaluate each charging station location on the selected list, a weighted point system was employed. Each of the seven factors affecting the evaluation of a given location was assigned a specific number of points, and a weight was also assigned to each factor based on its impact on the final location evaluation. Consequently, each location was assigned a weighted point score, which was calculated by multiplying the points for each factor by their respective weights, as specified in Eq. (1):

$$y = \sum_{j=1}^{7} w_i \cdot p_i \qquad (1)$$

where:
w_i – weight of the i-th factor,
p_i – points assigned to the location within the i-th factor.

The experts have identified seven factors that influence the assessment of charging station locations: investment lead time, investment cost, energy connection fee, application mode, RSA (Rest and Service Area) category, RSA size for heavy-duty (goods) vehicles, and RSA size for light-duty (passenger) vehicles. Experts have also defined the weights of factors and the relationships determining the allocation of specific point values within those factors. The maximum number of points assigned for each factor was 10. Each location could receive a maximum of 10 points.

The experts involved in determining the aforementioned factors represented the following entities: (1) a professional organization engaged in the development of zero-emission transport (Polish Alternative Fuels Association); (2) a higher education institution (Warsaw University of Technology), (3) central administration; (4) a distribution system operator; (5)a public charging station operator.

Individual factors influenced the assessment of charging station locations in the following way:

1. The investment lead time by the distribution system operator (DSO) which determined the possibility of investment implementation within the deadlines specified in AFIR regulations. The initial value assigned to the location for this factor was 10 points (as shown in table 3). Extending the investment lead time results in a reduction in the number of points awarded. If the investment lead time exceeded 52 months, the location received 0 points.

Table 3. The relationships defining the allocation of points as part of the first factor (Source: Own elaboration)

Investment lead time by the distribution system operator (DSO)	**Number of assigned points**
***T* (months)**	p_1
$T > 52$	0
$48 < T \leq 52$	1
$44 < T \leq 48$	2
$40 < T \leq 44$	3
$36 < T \leq 40$	4
$32 < T \leq 36$	5
$28 < T \leq 32$	6
$24 < T \leq 28$	7
$20 < T \leq 24$	8
$16 < T \leq 20$	9
$T \leq 16$	10

The weight of this factor was $w_1 = 0.20$.

2. The cost of investment borne by the DSO during the development of the energy network. The investment expenses included the total costs incurred for the expansion of the network as well as the costs necessary to build the connection. The initial position for the evaluation of this criterion was 10 points (Table 4). Increasing the investment cost results in a reduction in the number of points awarded. If the investment cost exceeded PLN 20 million, the location received 0 points.

Table 4. The relationships defining the allocation of points as part of the second factor (Source: Own elaboration)

Investment cost	**Number of assigned points**
***C* (Million PLN)**	p_2
$C > 20$	0
$18 < C \leq 20$	1
$16 < C \leq 18$	2
$14 < C \leq 16$	3
$12 < C \leq 14$	4
$10 < C \leq 12$	5
$8 < C \leq 10$	6
$6 < C \leq 8$	7
$4 < C \leq 6$	8
$2 < C \leq 4$	9
$C \leq 2$	10

The weight of this factor was $w_2 = 0.20$.

3. Energy connection fee which determines the costs that investors must incur for connecting the planned charging infrastructure to the power grid. The initial position for the evaluation of this criterion was 10 points. The allocation of points is presented in table 5. Increasing the energy connection fee results in a reduction in the number of points awarded. If the energy connection fee exceeded 100,000 PLN, the location received 0 point.

Table 5. The relationships defining the allocation of points as part of the third factor (Source: Own elaboration)

Energy connection fee E_f (thousand PLN)	**Number of assigned points p_3**
$E_f > 100$	0
$90 < E_f \leq 100$	1
$80 < E_f \leq 90$	2
$70 < E_f \leq 80$	3
$60 < E_f \leq 70$	4
$50 < E_f \leq 60$	5
$40 < E_f \leq 50$	6
$30 < E_f \leq 40$	7
$20 < E_f \leq 30$	8
$10 < E_f \leq 20$	9
$E_f \leq 10$	10

The weight of this factor was $w_3 = 0.10$.

4. The application mode, which informs about the interest of investors in each location. It defines if a potential investor has expressed interest in developing charging infrastructure in each location, in accordance with AFIR regulations. When assessing this criterion, the notification of a particular location by an investor who has expressed interest in the development of charging infrastructure on its premises was considered. The notified location received 10 points. The remaining locations received 0 points. The weight of this factor was $w_4 = 0.10$.
5. The RSA (Rest and Service Area) category determining the scope of functionality of a given location. Points were awarded to locations with category I and planned RSAs with an environmental decision providing the possibility of adapting the lease tender conditions to the requirements provided for in AFIR regulations. Category I RSAs and planned RSAs received 10 points. The remaining locations received 0 points. The weight of this factor was $w_5 = 0.10$.
6. The size of the RSA determining the number of available parking spaces adapted for LDVs. The condition is a significant factor that affects the throughput and functionality of a given location (Table 6). When evaluating the criterion, the number of parking spaces for LDVs (cars) was considered. The weight of this factor was $w_6 = 0.10$.
7. The size of the RSA determining the number of available parking spaces adapted for HDVs. The condition is a significant factor that affects the throughput and functionality of a given location. When evaluating the criterion, the number of parking spaces for HDVs (trucks) was analyzed (Table 6). The weight of this factor was $w_7 = 0.20$.

Table 6. The relationships defining the allocation of points as a part of the sixth and seventh factors (Source: Own elaboration)

Number of parking spaces for cars for p_6	**Number of parking space for trucks for p_7**	**Number of assigned points p_6, p_7**
0 ÷ 25	0 ÷ 10	0
26 ÷ 50	11 ÷ 20	1
51 ÷ 75	-	2
-	21 ÷ 30	3
76 ÷ 100	-	4
-	31 ÷ 40	5
101 ÷ 125	-	6
-	41 ÷ 50	7
126 ÷ 150	51 ÷ 60	8
-	61 ÷ 100	9
> 151	> 100	10

** The relationships presented in table 6 result from the characterization of RSAs located in Poland.*

4. Results and Discussion

The development of charging infrastructure on the core TEN-T network has been closely defined in AFIR regulations. Both the distribution of infrastructure every 60 km (and, in the case of heavy transport in the initial implementation stages, every 120 km) and the capacity that zones should have been goals to be achieved by individual member states.

Determining suitable locations for electric vehicle charging stations is particularly difficult due to its complexity, as complex legal, financial, technological, and organizational aspects must be considered. It is not possible to rely only on the key criterion, i.e., the distance criterion resulting from the AFIR requirements, but also time, financial and organizational criteria must be considered. At the same time, it is necessary to consider the situation that even though it is stated that the costs are very high and therefore the business justification for a given location of the charging station is questionable, due to the lack of any other possibility to meet the distance criterion, it will be necessary to commit this location for the setting of the electric vehicles charging station.

The article presents a five-stage approach to determining the location of electric vehicle charging stations in the Trans-European Transport Network (TEN-T), which considers objective location factors: meeting AFIR requirements, the specificity of the power system and the existing parking infrastructure. The proposed method has facilitated the execution of the project aimed at determining the suitable locations for charging infrastructure for both eLDVs and eHDVs along the roads within the TEN-T core network, in compliance with the AFIR requirements.

The distinctive feature of the proposed method, unlike existing approaches, involves not requiring comparative data, thereby on one hand enhancing result reliability, on the other hand leading to subjectivity. The proposed approach can serve as a valuable decision-making tool, helping decision-makers manage their inherent subjectivity while prioritizing criteria.

The essential element of the adopted method of solving the task is a multi-criteria evaluation system of each charging station location. Since the selection of locations localized on priority sections of the TEN- T network in accordance with the AFIR requirements was already made at the earlier stages of the developed approach, the system for the final assessment of the location of the electric vehicle charging infrastructure, operating within the 5th stage, concerns time, financial and organizational aspects. The main difficulty in this case was to properly determine the characteristic features of the location and the technique of determining their quantitative values. The choice of the seven criteria was determined by expert discussions held among individuals who possess an in-depth understanding of the distinctive features associated with the development of the infrastructure, automotive, and energy markets. Due to the complexity of the problem being solved and time constraints, using the knowledge of experts, specialists of various profiles, turned out to be the only possible solution in this case. The experts assigned weighting factors to the adopted criteria, the sum of which was 1. The weighting factors determined the importance of individual criteria in the final assessment of the location. Experts also defined relationships determining the allocation of specific point values within individual criteria. The maximum number of points assigned for each criterion was 10. As a result of the adopted multi-criteria evaluation system, each location could receive a maximum of 10 points.

When developing the time criterion, the schedule for implementing the investment obligations imposed by AFIR was primarily considered. Under this regulation, goals have been set for the TEN-T core network, covering three distinct timeframes: until the end of 2025, until the end of 2027, and until the end of 2030. It is noteworthy that the LDV objectives stipulate 100% electrification of locations by the end of 2025. Furthermore, by the end of 2030, the locations initially electrified by the end of 2025 are anticipated to have higher power capacity. In practical terms, this necessitates the timely completion of connection investments by the end of 2025, ensuring full coverage for LDV and 15% for HDV. Due to the great importance of the time criterion, the assigned weighting factor has a high value, and the points are differentiated with four-month precision in relation to the investment lead time. It is worth noting that the allocation of point values under the time criterion considered experiences gained in similar investments, particularly in the context of charging stations, and data obtained from business entities.

When formulating the financial criteria, closely related to the cost of the investment in electric vehicle charging stations, the extensive experience of experts in carrying out numerous similar investments was considered. The technique of assessing the location by the operators of the distribution system and charging stations was also considered. As a result, financial criteria hold great practical significance, aiming to guide the selection of locations that maximize cost-effectiveness within the allocated budget.
An example of the importance of organizational criteria are the criteria relating to the number of parking spaces available at the charging station, adapted for LDVs (cars) and HDVs (trucks).
When establishing the relationships determining the allocation of specific point values under the sixth and seventh criteria, a distinct point range was adopted, with one range for the number of parking spaces for trucks (incrementing every 10) and the other for cars (incrementing every 25). In addition, the criterion regarding the number of available parking spaces suitable for HDVs is given a double weighting factor. This differentiation was driven by the unique nature of facilities like Rest and Service Area (RSA) in Poland and a comprehensive analysis of the actual number of parking spaces available for LDVs and HDVs at all the RSA locations across the country. Generally, such facilities tend to experience frequent congestion, especially locations with many stopped HDVs. The electrification of a specific number of parking spaces entails temporarily excluding them from their primary function, as only electric vehicles will be able to occupy these spaces, and solely for the duration of the charging process. In practice, this may mean that some locations will require expansion and others will be completely omitted.
Considering the greater number of existing parking spaces dedicated to LDVs, the criterion dedicated to HDVs is much more important than the criterion dedicated to LDVs.
As a result of using the developed approach, a list of 188 locations suitable for the construction of charging stations for both LDVs and HDVs by 2030 was created. The top-scoring location received a score of 7.9. These locations are expected to meet the AFIR requirements for LDVs by 2025. For HDVs, out of the 188 identified locations that should be operational in 2030, 27 should be implemented by 2025 and a total of 71 locations should be in operational active by 2027 (Fig. 5).
The completed project, which is the first of its kind in Poland, enabled the identification of investments necessary to meet AFIR standards. The key findings of this project can be summarized as follows:

– In most cases, the scenario assuming fulfilment of the obligations under AFIR regulations for 2025 is feasible.
– The scenario for implementing the obligations under AFIR regulations for 2030 is feasible, but DSOs need to start investing in 2023.
– DSOs do not have any spare capacity in distribution networks located near RSAs.
– The 2030 requirements will necessitate investments in deep network expansion, including Main Power Supply Points.

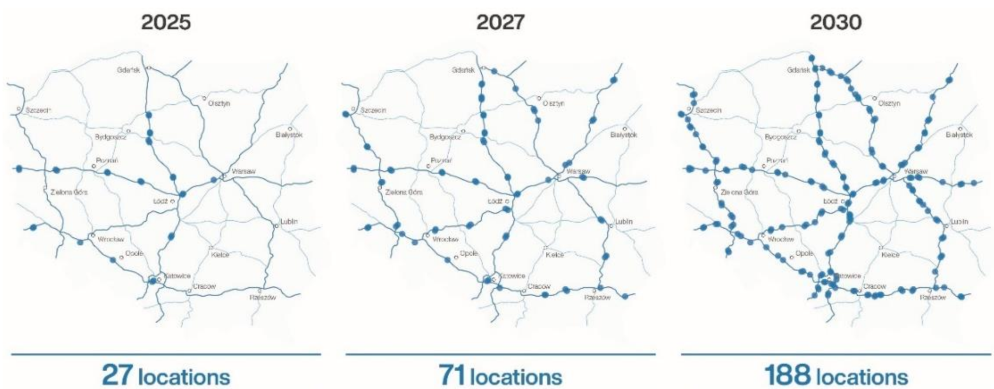

Fig. 5. A list of recommended locations on the TEN-T core network for the deployment of charging infrastructure for LDVs and HDVs in 2030 (Source: Own elaboration)

Poland will face several future sustainable challenges and opportunities in the realm of charging infrastructure development for eLDVs and eHDVs. The main challenges and opportunities related to the development of electromobility infrastructure in Poland can be summarized as follows:

- The development of e-mobility necessitates substantial investment in electricity infrastructure to support an adequate number of charging stations. The capacity of Distribution System Operators (DSOs) is strongly constrained by current limitations in grid expansion needs, technology, technical standards, inflation, and a lack of strategic investments.
- The growth of the distribution network will reinforce the energy infrastructure, enhance the appeal of industrial areas, and contribute to improving the connection of renewable energy sources (RES) to the grid.
- The successful implementation of the requirements specified in AFIR regulations mandates the commitment of DSOs to construct infrastructure up to the Rest and Service Area (RSA) boundary, with the need for dedicated financial resources.

This study is significant to contribute to the theoretical implications because that it might accomplish a few research objectives.

First, the presented method highlights utilitarian aspects through simple calculation and selection of factors that are can be expanded. This approach can be adopted for academic to extend it about sophisticated quantitative data-based sustainability assessment methods of applying segmentation to extract some part of EV-infrastructure to be evaluated (e.g., for establishing transport emissions, assessing factors along the EV charging infrastructure). AHP (Saaty, 1990, 2008), FAHP (Ju et al., 2019) or FUCOM- F (Pamucar et al., 2021) can be applied to receive consistency in relative weights of criteria of location selection considering sustainability features or/and compare these criteria with alternative methodological approaches. Thanks to that, the use of multi-criteria decision making (MCDM) methods can contribute to evaluation methods repository from the scientific literature. The approaches might address to make decisions for the sustainability of transport by business partners, investors, and policy makers where a solid scientific evaluation is not required.

Second, large-scale EV charging stations integration to the electricity national grid can be assessed, also in terms of sustainability by looking at the impact of the distribution network on sustainable transport.

Third, the uptake of EV charging stations is dependent from the involvement of both the public and private sectors to achieve development of the required infrastructure for assessment and then large-scale EV deployment (LaMonaca & Ryan, 2022).

Fourth, it may provide energy policy or energy management strategy for optimizing load demand of EV on the electricity distribution network in terms of sustainable transport. This implies a likely interdependency between energy distribution network and sustainability, cost, and energy management. It can also contribute better understanding of the relationships between element of the system at a finer scale. Implementing these findings can greatly facilitate zero-emission vehicle operation and bring Poland closer to Western European countries in zero-emission transport development. For a sustainable future, it is vital to promote sustainable mobility in Poland, measuring EV infrastructure against transport system sustainability (Gallo & Marinelli, 2020). Aligning electric mobility with Sustainable Development Goals (SDGs) promotes transport decarbonization, sustainable growth (SDG 9), and the integration of transport systems into European markets (SDG 9). Poland should commit to providing cost-effective, sustainable transportation systems for high-power EVs, meeting current market demand (SDG 11).

In summary, the developed approach provides a comprehensive solution to address the challenges of sustainable EV charging infrastructure, taking into account legal, financial, technical, and organizational aspects, and supports the EU's efforts to combat climate change and promote sustainable transportation (Hussain et al., 2020; Kene et al., 2021; Kong & Liu, 2017; Mock & Diaz, 2021; Sohail et al., 2021).

5. Conclusion

This research has developed the original and comprehensive five-stage expert approach integrating legal considerations to guide the selection of the electric vehicles charging station location across Poland`s TEN-T core network. The incorporation of a law-based method within the framework of a sustainable policies underscores the importance of

AFIR regulations and their effective implementation, aligning with the objectives of this paper. Using the developed approach, the authors compiled a catalogue of 188 potential locations for constructing charging stations serving both LDVs and HDVs by 2030. Among these, the highest-rated location achieved a score of 7.9 from 10. These locations should meet AFIR requirements for LDVs by 2025. For HDVs, 27 of these locations should be operational by 2025, and a total of 71 by 2027.

This study yields several overarching conclusions, as follows:

- The proposed approach for EV charging station selection is both versatile and innovative, easy to understand designed to enhance decision-making by adhering to AFIR regulations. This approach can be easily adapted and seamlessly integrated with various other methodologies like AHP or enhanced version of AHP BWM (Rezaei, 2015) to create a more comprehensive attribute weight calculation algorithm, enhancing the decision-making process.
- The method enables the practical use of the knowledge of subject experts which was not considered yet in the available literature on selection of electric vehicle charging.
- The use of the proposed approach increases result consistency and reliability, while reducing processing time and effort.
- The suggested method has the potential for wide applications and can be utilized across various measurement scales to represent expert preferences contributing to the theoretical implications due to its universality.
- The precise defined guidelines are imperative for both Distribution System Operators (DSOs) and the market, enabling Poland to meet the outlined AFIR requirements effectively.

However, the developed approach also has limitations, including a relatively simple selection process based on subjective expert criteria method. In addition, complex data may arise during evaluations due to uncertain decision-makers and diverse attributes. Therefore, future research should prioritize divergent and integrated methods influenced by environmental, social, economic, and technological sustainability aspects for widespread electric vehicle adoption in Poland.

Abbreviations

ACEA – European Automobile Manufacturers' Association
AFIR – Regulation of the European Parliament and of the Council on the deployment of alternative fuels infrastructure
BEV – Battery Electric Vehicle
DSO – Distribution System Operator
EEA – European Environment Agency
eHDV – electric Heavy-Duty Vehicle
eLDV – electric Light-Duty Vehicle
EU – European Union
EV – Electric Vehicle
HDV – Heavy-Duty Vehicle
HPC – High Power Charger
ICE – Internal Combustion Engine
LDV – Light-Duty Vehicle
M1 – Passenger vehicle having not more than eight seats in addition to the driver's seat
N1 – Vehicle designed and constructed for the carriage of goods and having a maximum laden mass not exceeding 3.5 tons
OEM – Original Equipment Manufacturer
PHEV – Plug-in Hybrid Electric Vehicle
PSPA – Polish Alternative Fuels Association
TEN-T – Trans-European Transport Network
RSA – Rest and Service Area

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