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MODEL FOR BUILDING A CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES ALONG BULGARIA'S REPUBLICAN HIGHWAY NETWORK

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ABSTRACT
The electrification of mobility has been identified as a precondition for successfully reducing dependence on fossil fuels, it also contributes to the reduction of air and noise pollution (Lan, 2023). The reduction of harmful emissions on a global scale requires the mobility industry to simultaneously invest in and study low-carbon energy technology and infrastructure (Shahzad, 2024). When it comes to determining the locality of the charging infrastructure, one of the challenges is the capacity of the vehicles' batteries and the charging stations. The approach for determining the charging points will be approbated for long-distance travel along the republican highway network. Solutions and possible scenarios for upgrading the transport sector and the associated guarantee of energy resources will be provided through a multidisciplinary analysis which includes current and future necessities for accessible charging infrastructure. This will be based on the calculation of the average distance from the starting point to the necessary station depending on the battery capacity, the amount of energy which can be charged in a 30-40-minute range, as well as the condition that the battery is in.

Keywords: *charging infrastructure, electric vehicles, charging stations, transport networks, decarbonisation*

1. INTRODUCTION

In the conditions of the Green Deal, the spread of electromobility is a key element in the efforts to reduce harmful emissions which are set in the Paris Agreement and the objectives of the EU (EEA, 2024). The goal of the "Green Pact" is to reduce the amount of harmful emissions of greenhouse gases to 55-60% by 2030 and to 95% by 2050, i.e. to achieve a carbon neutral economy in Europe in terms of climate (CT, 2021). The reduction of harmful emissions on a global scale requires the mobility industry to simultaneously invest in and study low-carbon energy technology and infrastructure (Shahzad, 2024). One way to significantly reduce carbon emissions is to switch to alternative fuels in motor transport (NP Group, 2023). The allocation of energy resources, energy efficiency and the changing demand models are a challenge for electric vehicle manufacturers. The goal in the strategy for intelligent, sustainable and inclusive growth is to increase competitiveness and energy security by reducing the dependency on fossil fuels, thus achieving more effective use of resources and energy, which also involves a sustainable strategy for powering vehicles, as well as their appropriate infrastructure, through alternative sources. Electric energy, hydrogen, biofuels, natural gas and liquefied petroleum gas can be viewed as such sources, as they presently have the potential for long-term and sustainable use, as a complementary (two-fuel) system at first. Presently, electric energy is viewed as the most promising technology for limiting greenhouse emissions in the transport sector (ME, 2024). Its nature is deduced from the use of electric engines for vehicle pro-

pulsion. Additional advantages of electromobility include: increased energy efficiency, reduction of harmful emissions in the atmosphere, and reduced noise pollution (Idris & Rahman Razak, 2025). Innovative decisions in the incorporation of new technology related to electromobility are key in the development of the electric vehicle market and the charging infrastructure. In addition to playing a fundamental role in the competition with conventional cars and the existing infrastructure, they, along with battery capacity, will also be the key to the future choices of consumers. It is precisely the readjustment of consumers to the new type of mobility that will be one of the many unknown factors in the emergence of electric vehicles. Other such factors involve the development of technology for energy charging of vehicles, the costs for new production, the various propulsion technologies, and especially the final costs of consumers for vehicle acquisition and maintenance. Nowadays the two biggest and most fundamental problems that influence the selection of the type of propulsion energy are the run (the battery capacity) and the availability of an appropriate charging infrastructure along the primary republican highway network. Taking into account the ever-growing number of electric vehicles which are being registered in Bulgaria, especially over the last 5 years, this raises the question of how dense the charging infrastructure needs to be. When it comes to determining the locality of the charging infrastructure, one of the challenges is the capacity of the vehicles' batteries and the charging stations. The approach for determining the charging points will be approbated for long-distance travel along the republican highway network. The model excludes everyday travel in an urban environment where 90% of the charging happens in home conditions or at workplaces.

2.LITERATURE REVIEW

The strategy for developing the charging infrastructure in Bulgaria cannot be based on the number of registered electric vehicles but rather by preliminarily providing the backbone of the necessary accessible infrastructure which will respond to the growing emergence of electric mobility. When determining the minimum mandatory national goals of EU countries for expanding the alternative fuel infrastructure in accordance with "Fit for 55", one of the requirements is the availability of charging stations at every 60 km for cars and every 120 km for trucks (EP, 2023). Additionally, ultrafast charging stations with at least 150 kW of power will have to be installed, as this will guarantee that 1,3 kW of output power will be provided for each registered electric car by a publicly accessible charging infrastructure (EC, 2023). These charging stations need to have a capacity of 400 kW along the routes of the primary TEN-T network. In accordance with the "Transport Connectivity" program, 10 million BGN are envisioned for charging hubs for electric vehicles along the primary and comprehensive Trans-European Transport Network (MT, 2024). The reason for the relatively small share of electric vehicles in Bulgaria has less to do with their high prices and the lack of subsidies, but more so with the lack of a sufficiently well-developed charging infrastructure (Rachev, 2019). By 2030 the number of necessary public charging stations in the EU will exceed 2 million, whereas the expected number in Bulgaria for the same period is 10 000 (CEER, 2023). According to Dimo Kolchev, CEO of Eldrive, about 25-30% of electric cars in Bulgaria are charged in the public network, the rest are charged at home or in the office (Kolchev, 2025). As of 2025, there are nearly 3,000 charging points in Bulgaria, but only a little over 500 are fast-charging, and more than half of them have a power of 22 to 50kW, which requires a longer charging time (Boceva, 2025). Fair access to a charging infrastructure will help form target strategies for its expansion as well as accelerated emergence of electromobility (Burra, 2024). Electric vehicles add large and dynamic loads to the network, requiring adaptation to the capacity and integration of intelligent systems for consumption management. The impact of EVs on the overall energy system will depend on when and how EV users charge their vehicles (Kareta, 2022).

3.METHODOLOGY

The approach for making decisions about the future development of electromobility in Bulgaria involves a step-by-step examination of the current state of the charging infrastructure and its potential intelligent construction in the context of the energy transformation of motor transport. Solutions and possible scenarios for upgrading the transport sector and the associated guarantee of energy resources will be provided through a multidisciplinary analysis which includes current and future

necessities for accessible charging infrastructure. This will be based on the calculation of the average distance from the starting point to the necessary station depending on the battery capacity, the amount of energy which can be charged in a 20-30-minute range, as well as the condition that the battery is in. To that end, scientific publications in the field, regulations and future planned applications of new technology will be reviewed. The economic capabilities will be analyzed by identifying the benefits and disadvantages of creating the charging infrastructure for the purposes of developing a universal approach.

4.STATE AND DEVELOPMENT OF CHARGING INFRASTRUCTURE IN BULGARIA

The creation of a charging infrastructure is the primary challenge that Bulgaria faces in regards to switching to electric mobility and by extension to a motor park with absolutely zero emissions by 2050 (ECA, 2021/5). However, there are several factors which are unfavorable to future users of electric vehicles, such as limited accessibility, insufficient charging speed, and the quality of the utilized equipment (Zhang, 2020). In that regard, it is imperative that the charging of electric vehicles be as accessible and easy as the fueling of conventional cars. The goal is to make traveling by electric vehicles problem-free not just along the republican highway network, but within the EU as a whole. In order to achieve the set goal, the following two-fold problem needs to be solved – accelerating the emergence of electric vehicles requires an established charging infrastructure along the primary TEN-T network; on the other hand, however, investments in such an infrastructure requires more security in regards to the degree of emergence of this type of vehicles (Nurgaliuly & Smagulova, 2025). This is also one of the fundamental challenges that the larger-scale (wider) emergence of electromobility in the EU faces. Without an established and accessible infrastructure where electric vehicles can be easily recharged at a reasonable price and, most importantly, at a reasonable time, it will be difficult to achieve commercial success in the realization of this type of vehicle. While the risk of the vehicle ending up blocked without energy while traversing is minimum, conventional cars have not faced such a problem during their life cycle.

Charging stations play a key role in the switch to electric mobility by providing a convenient and effective way of charging. The advancements in technology make charging stations more effective, which in turn contributes to increasing their number on the basis of faster charging, intelligent management and remote control and monitoring.

5.DATA AND ANALYSIS

In the past 10 years Bulgaria has made wide-range developments in its alternating current (AC) and direct current (DC) charging infrastructure. Currently, there are approximately 2000 public charging stations in the entire country, approximately 15% of which are located within the capital (VT, 2025). Public charging stations provide non-discriminatory access to all consumers in accordance with Directive 2014/94/ES (EU, 2014). According to Traffic Police data, the number of registered electric vehicles in Bulgaria as of March 31 2025 is 19 630 (Traffic Police, 2025). The average storage capacity of a lithium-ion battery is 60 kW, which is equal to approximately 1200 MW of the total amount of energy necessary for charging. This in turn is equal to 1/4 of the total amount of electricity consumed in Bulgaria, which represents a significant percentage of the self-capacitance for production of electric energy in the country. This significant share needs to be corrected by taking into account the simultaneity coefficient which varies between 4 and 11%, with the charging period reaching its peak during the night.

The study only takes into account the charging of vehicles which traverse distances of over 150 km, i.e. traveling between various populated areas. Everyday travel within an urban environment has been excluded from the analysis due to the fact that more than 80% of electric vehicle owners charge their vehicles with home-based charging stations during the night, meaning that they practically do not use public ones. A distance of 150 km (Sofia – Plovdiv) is viewed as the minimum traversed distance, whereas a distance 460 km (Sofia – Varna) is viewed as the maximum one. That way, it is accepted that the average distance that an electric vehicle will traverse is 300 km. This will serve as a basis for analysis of the demand for charging along Bulgaria's republic highway network. The num-

ber of cars in Bulgaria (in total and solely electric ones) for the April 1 2021 – April 1 2025 period (data.egov.bg, 2025) is presented in Table 1.

Table 1. Ratio of Electric Vehicles to the Total Number of Cars

years	total number of cars	EV's	% of electric to total	percentage growth
1.4.2021	2 765 397	2 348	0,0008	
1.4.2022	2 815 628	3 835	0,001	39%
1.4.2023	2 899 264	7 427	0,002	48%
1.4.2024	3 014 969	13 052	0,004	43%
1.4.2025	3 141 954	19 630	0,006	33%

Source: data.egov.bg

The data from the table shows that, despite an 88% rise in the number of electric vehicles for the entire period, a trend of decline in the number of registered electric vehicles in comparison to each previous year has been observed in the last three years. Additionally, it is quite striking that the number of registered electric vehicles in regards to the total number of cars is negligibly small.

A new test for examining and measuring fuel economy, electric vehicle run and emissions was introduced in 2017. The new WLTP (Worldwide Harmonized Light Vehicle Test Procedure) has replaced the old NEDC (New European Driving Cycle) standard. The introduction of this new method of testing cars has led to more accurate and realistic data about energy expenditure and emissions. The elements which are taken during the test include: Rolling resistance; Air resistance; Different engine and gearbox combinations; and Optional equipment (VCA, 2021). Different car brands have different models of electric vehicles with different capacity and range. The WLTP characteristics of some models, in accordance with the average mileage calculated above, are shown in Table 2.

Table 2. WLTP Characteristics of Car Models

models	range (km)	charging time from 20% to 80% (minutes)	average consumption (kW)	battery capacity (kW)
Dacia Spring	225	45	14,6	50
Renault Zoe	325	50	16	52
BMW i3	235	35	16,1	38
Opel Ampera E	345	40	16,8	58
Peugeot E 2008	250	30	18	45
Hyundai Kona	400	45	16	64
Volkswagen ID.3	350	30	16,6	58
Tesla 3	386	30	16	62
Skoda ENYAQ	330	50	17,6	58

Sources: EVpoint (EV, 2025) Dacia Spring (Dacia, 2025)

The following inferences can be made on the basis of the data in the table for the purposes of the study:

- the average run of an electric vehicle is approximately 320 km;
- the average charging time is 40 minutes;
- the average consumption of electricity for a run of 100 km is 16,5 kW per 100 km;
- the average battery capacity is 54 kW.

The average range of electric vehicles is reduced by 20% because when the remainder of the battery capacity is 20%, all manufacturers recommend charging, plus another 10% for additional battery consumers in cold and hot weather which affects the battery capacity. Upon completing the calculations, it is estimated that the average range of one car is 220 km. During the first charging, only 60% of the capacity (80 – 20) can be added at an average charging time of 40 minutes, which is equal to a hypothetical additional run of 130 km. If a second charging is required, it will be after approximately 100 km (130 – 20%) – the quantified power between the first and second charging is only 60% of the battery capacity.

The traffic along the main roads in Bulgaria, which have a total length of approximately 4000 km (first-class – 2900, and highways – 840) is unevenly distributed in the network (NSI, 2025). There are time variations in the demand – the intensity during workdays and weekends/holidays, during morning, noon and evening hours is different, which creates additional pressure in the country's transport network. Said time variations create an imbalance in the demand for a charging infrastructure, meaning that the number of necessary charging points along the main roads needs to be determined on the basis of the maximum intensity during peak days and hours. This in turn will guarantee the high quality of the provided services, which is at the basis of charging services for consumers of electrical mobility. These variations in the demand for a charging infrastructure and various routes from the perspective of distances which can be traversed with one charging and a reduced second one as a capacity can be presented through queuing models (Soylu, 2016). These models evaluate the use of charging points for service depending on the allocation of time during charging. Of significant importance for the larger-scale emergence of electric vehicles in Bulgaria are several factors:

- the amount of time necessary to charge the battery;
- the amount of waiting time at the charging station (if there are other cars);
- the availability of an ultrafast charging station;
- the high and sometimes unknown prices per kW of energy.

An author's study among users of electric vehicles shows that the low charging costs are at the basis of the criteria for purchasing cars with electric traction. The other criteria involve convenient locations (in terms of shopping or workplaces) and the availability of ultrafast charging stations (DC).

This approach allows us to calculate the locality of the charging infrastructure along the republican highway network and the necessary number of charging points on the basis of traffic and arrival frequency. The deployment distance of charging stations, their power and the number of necessary charging connectors will be determined by the number of cars which will arrive during peak days and hours and require simultaneous charging. The goal is to minimize waiting time and charging time – the use of charging stations should be between 80 and 100%, and the total waiting time should not exceed 30-40 minutes.

6.RESULTS

Applying the queueing model, based on the frequency of arrival of electric vehicles at charging points during peak loads (holidays and weekends) and the corresponding levels of use (arrival time and battery capacity and condition) will allow us to calculate the required number of points (not the number of charging stations) for charging. With an average number of vehicle arrivals per hour – 5, an average number of charging per hour per point – 2 and an average waiting time of 8 to 10 minutes. In a scenario of 35 000 electric vehicles in 2026 calculated on the basis of the data in Table 1, as well as an average number of people traveling in them during peak days and hours plus transiting foreign vehicles 10500 (30%), at a minimum waiting time of 9 minutes and average charging time of 35 minutes, 460 ultrafast charging stations (DC) with a capacity of over 350 kW are required, each with 2 connectors.

The recommended distance is between 70 and 90 km along the primary network – first-class roads and highway network. As of April 2025, ultrafast charging stations in Bulgaria are a little over 500 in total and only 20% of them have a capacity of over 200 kW (VT, 2025). Another peculiarity is that more than half of them are located in the city of Sofia and its surrounding areas. The relation between the number of charging points, the waiting time and their spatial arrangement along the republican highway network is crucial in analyzing customer preferences, especially in the context of the growing number of home charging stations. Transparent pricing, the unification of various charging connectors and the integration of electric vehicles in the country's common electrical grid in the context of ecological goals is another important topic. To have a sustainable development of electromobility, it is necessary to build publicly accessible charging stations, located on the main republican roads, no more than 70-90 km apart in both directions of travel. Each of these stations must have a capacity of at least 350kW and the presence of two charging points, each with 150kW.

In summary, the study shows that the charging infrastructure in Bulgaria is not only insufficient but also distributed unevenly along the republican highway network. The creation of new charging stations should include a geographical dimension, i.e. average distance between charging points, incorporation of ultrafast charging points, various methods of payment and provision of accurate and appropriate information for consumers.

7. CONCLUSION

The development of the charging infrastructure needs to be in synergy with technological development – life cycle of various drive systems, analysis of building costs (their physical building and energy costs during exploitation) and interface (hardware and software) for charging with direct current (DC). The development of a charging infrastructure should not be to the detriment of the existing one, as society and enterprises need to continue having access to conventional fuels for the existing motor fleet.

The article examines an approach for the development of the charging infrastructure which is based on the demand regarding long-distance travel (over 150 km) on the main roads of the TEN-T network. The methodology is based on the assumption that a comparatively slow rise is observed in the demand for electric vehicles capable of long-distance travel and that more than 70% of consumers use home or office charging. While the development of the charging infrastructure is included in the prerogatives of every country, the approaches in regards to its creation, as well as the support for its expansion vary. There is a lack of a harmonized pan-European infrastructure due to high initial costs and the lack of critical mass on behalf of consumers, which causes private investors to act with restraint. The fact that the standards regarding the switch-in technology (interface) of charging stations are not uniform poses another problem. Securing an infrastructure which is interoperable, reliable and convenient for customers is the key to the sustainable creation of charging stations. A fundamental argument against the larger-scale integration of electromobility in Bulgaria is consumers' reluctance to purchase electric vehicles with an average run of 300-320 km and the uncertainty in the pricing of public stations and the low density of their location along the main transport network. An essential element of this future development of electromobility involves manufacturers who will need to design cars with an autonomous run of at least 500 km, and state institutions need to create conditions for building a charging infrastructure which will make travel secure and reliable.

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