

Drivers of Electric Vehicle Market Penetration: Empirical Findings from Bulgaria

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Abstract: This study investigates the impact of government tax policy on the development of sustainable transport in Bulgaria by analysing the drivers of electric vehicle (EV) market penetration. Using a balanced panel dataset covering the period 2018–2023 for selected Central and Eastern European countries (CEECs), a two-way fixed effects panel regression model is employed to account for both country-specific and time-specific unobserved heterogeneity. The results indicate that higher economic development, proxied by GDP per capita in PPS, significantly increases EV market share, highlighting affordability as a fundamental driver of electric mobility adoption. Population density is also found to have a positive, statistically significant effect, suggesting that urbanisation and spatial efficiency facilitate EV diffusion by enabling shorter travel distances and a more effective use of infrastructure. In contrast, the analysis does not provide sufficient evidence that the absolute number of public charging stations directly influences EV market share over time within countries. Furthermore, the estimated country fixed effects reveal substantial cross-country heterogeneity in EV adoption, reflecting persistent structural and institutional differences beyond observable economic and infrastructural factors. These findings underscore that EV adoption is a multifaceted process shaped by the interaction of economic capacity, spatial structure, and country-specific conditions.

Keywords: Electric vehicles, market penetration, government support, sustainable transport, fiscal policy

1. Introduction and Literature Review

In recent years, the transport sector in Europe has independently generated over 20% of greenhouse gas emissions. Its relative share has ranked it second after the energy industry for many years. The

latest data [1] already confirms its leading position, ranking it first and making it the sector that generates the most greenhouse gases. Its relative share amounts to 26.2%, compared to 24.9% for Energy Industries, 19.6% for Industry, 12.6% for Agriculture, and smaller shares for other sectors. According to [1], thanks to its consistent policies, the EU has successfully reduced greenhouse gas emissions over the past few decades. The only exception is emissions generated by the transport sector. Reducing transport sector emissions is critical in achieving environmental sustainability and climate neutrality. This can be accomplished by imposing increasingly stringent standards and norms regarding the environmental compatibility of vehicles.

The introduction of the Euro 7 standard in 2025 for cars and in 2027 for trucks and buses will impose even stricter requirements on the production of new vehicles, which older conventional cars will not meet. This will significantly transform the vehicle market, steering it increasingly toward the production of electric or at least hybrid vehicles. However, given their higher prices and unique operational characteristics, their adoption requires active, targeted state support. The transition to sustainable transport and climate neutrality is a central goal outlined in [2], which sets CO₂ emission standards for new passenger cars and light commercial vehicles (vans). In 2023, [3] introduces even stricter CO₂ emission standards for new passenger cars and light commercial vehicles, aligned with the EU's more ambitious climate goals. Furthermore, in 2024, [4] imposes even stricter CO₂ emission requirements for heavy-duty vehicles. The primary objective of these legislative measures is to make road transport more environmentally friendly, thereby reducing greenhouse gas emissions and meeting the targets of the Paris Agreement. EVs play a pivotal and promising role in meeting these stringent requirements and decarbonising the transport sector, mainly when supported by appropriate support [5]. These include Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), which are increasingly gaining traction in the European market. As of 2024, their share reached 19% of the newly purchased passenger car market. However, their overall share in the European vehicle fleet remains slightly above 2%. Consequently, to achieve the EU's climate neutrality targets by 2050, a significant increase in the electric vehicle fleet is required.

This growth can only be achieved through active state support and intervention, as there is a strong correlation between financial incentives and EV market share [6,7]. Such support may include direct investments in production, development of charging infrastructure, and similar initiatives. A significant barrier to purchasing an electric vehicle is its significantly higher cost compared to conventional vehicles. The price gap varies by model and market segment. For example, in the Bulgarian market, electric cars are approximately 56% more expensive, with some models priced over 70% higher. According to [8], this gap ranges from 40% to over 100%. Due to this cost disparity, active government policy, including financial incentives and additional measures, is crucial to promoting EV sales.

According to [9], a key strategy for tax differentiation is increasing the tax burden on high-emission vehicles while lowering it for low-emission ones. However, achieving results through higher taxes on high-emission vehicles is more challenging in countries like Bulgaria, where living standards are low, purchasing power is limited, and the vehicle fleet is ageing. Tax relief for vehicles with zero or low emissions can have a more significant impact. Implementing such tax incentives inevitably reduces government revenues, creating substantial challenges for balancing the budget. However, these measures are crucial, especially in the early stages of EV market development in each country, when significant differences still exist between conventional and electric vehicles. These disparities arise from various factors, including price, uncertainty, and infrastructure constraints. Over time, as these differences diminish and the market becomes more balanced, the need for government intervention reduces. Hence, such policies should be temporary and time-limited, designed to bridge the initial gap and support market growth until the transition becomes self-sustaining.

Previous studies [10,11] have analysed the relationship between the purchase of electric vehicles and indicators such as tax reliefs, subsidies, free parking, bus lane access, reduced vehicle license fees, free ferry tickets, fuel prices, owner income, education, and the owner's environmentalism [12-14] and others. [15,16] identifies statistically significant determinants of BEV sales across Europe using multiple regression and cluster analyses. However, empirical evidence remains limited for Eastern European countries, especially Bulgaria, where this study aims to contribute by examining the influence of income, charging infrastructure, and population density on EV penetration from 2018 to 2023.

2. Data and Methods

The primary objective of the research is to explore and assess some key socio-economic and infrastructural factors that can effectively drive the growth of the EV market share in the context of sustainable transport. The study incorporates data from international and national institutions, including the European Environment Agency (EEA), the European Alternative Fuels Observatory (EAFO), the European Automobile Manufacturers' Association (ACEA) and Eurostat. Various methods are employed for data processing and analysis, including historical and chronological analysis, comparative and critical analysis, content analysis, inductive and deductive methods, quantitative analysis of dependencies, graphical analysis, and Panel data analysis.

To address the limited time-series length for a single-country regression and to improve statistical validity, the study employs a balanced panel dataset covering six CEECs - Bulgaria, Romania, Hungary, Slovakia, Czechia, and Poland over the period 2018-2023. The determinants of EV market penetration are estimated using a two-way fixed effects panel regression model, which controls for unobserved country-specific heterogeneity (α_i) and common time effects (λ_t). This specification

isolates within-country changes over time and mitigates omitted-variable bias arising from time-invariant national characteristics and EU-wide shocks. Robust standard errors clustered at the country level are reported to account for heteroskedasticity and within-country serial correlation. The dependent variable is the EV market share. The indicator used in the analysis is based on ACEA statistics. These data cover newly registered light passenger vehicles with a gross vehicle weight of up to approximately 3.5 tonnes. The explanatory variables are selected based on economic theory and prior empirical evidence on EV adoption. They capture infrastructure availability, measured as the number of charging points, economic development, measured as GDP per capita in PPS, and population density, measured as persons per square kilometre. Although the relatively short six-year research period limits the analysis's scope, the lack of long-term statistics on EVs, especially in CEECs, remains a current constraint. This represents one of the study's limitations.

The number of charging points for ECVs per country is selected as an independent variable because it significantly influences purchase decisions; inadequate or limited infrastructure can significantly impede sales. The theory of range anxiety and access to charging points are the two key barriers to purchasing EVs. A well-functioning infrastructure reduces transaction costs and increases vehicle utility. Data from ACEA has been used in absolute terms. While relative indicators such as charging stations per 1,000 vehicles or per area may provide a more detailed picture of infrastructure accessibility, such indicators require combining several statistical sources and were therefore not included in the present analysis.

Affordability is the next selected independent indicator. EVs are capital-intensive goods, and demand is sensitive to income and purchasing power. To measure it, Eurostat data for GDP per capita in PPS have been used, as they make the data comparable across countries and correct for price differences. Additionally, higher incomes often accompany better education, which enables the purchase of more expensive electric vehicles. Some studies analyse the impact of education as a factor positively influencing the decision to buy such vehicles [17-19]. On the other hand, [20,21] reports no significant relationship between the indicators mentioned.

Population density is the next selected independent indicator measured as persons per km². Higher population density implies shorter travel distances, easier coverage with charging points, and a higher share of urban trips. Data from Eurostat have been used.

Based on the criteria presented, EV market share is modelled as a function of charging infrastructure, economic development, and population density as follows:

$$MSEV = f(NCP, GDP_PPS, PD), \quad [-] \quad (1)$$

where: *MSEV* is Market Share of EV; *NCP* is Number of Charging Points; *GDP in PPS* denotes Gross Domestic Product in Purchasing Power Standard; *PD* is Population Density

Empirically, this relationship is estimated using a two-way fixed effects panel regression:

$$MSEV = \alpha_i + \lambda t + \beta_1 * NCP + \beta_2 * GDP_PPS + \beta_3 * PD, \quad [-] \quad (2)$$

where β_1 , β_2 , and β_3 are parameters measuring the within-country effects of the respective factors over time.

The theoretical expectation regarding the signs of the parameters is: $\beta_1 > 0$, $\beta_2 > 0$, $\beta_3 > 0$

The selection of these indicators allows us to formulate the following hypotheses, which will be subsequently analysed:

Hypothesis 1 (H1): A higher number of charging stations positively influences purchasing electric vehicles and increases their market share.

Hypothesis 2 (H2): Higher economic development, proxied by GDP per capita in PPS, positively affects the purchase of electric vehicles and increases their market share.

Hypothesis 3 (H3): Higher population density supports electric vehicle diffusion through urbanisation and spatial efficiency effects.

3. Results

Studying such a relationship is particularly relevant for countries like Bulgaria, where affordability constraints and limited charging infrastructure remain significant barriers to EV adoption.

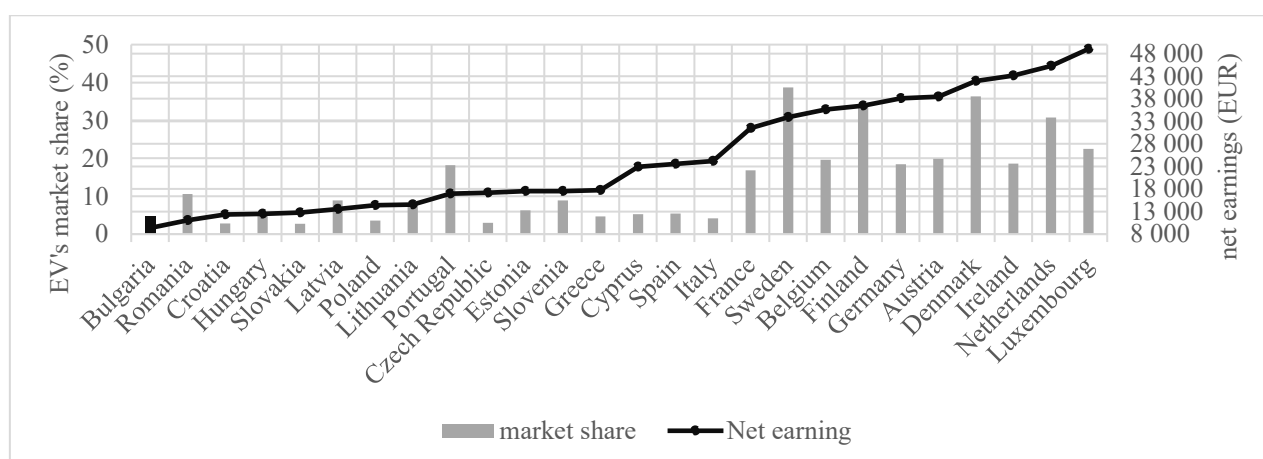


Fig. 1 ECV market share vs net earnings of a single person without children earning 100% of the average earnings in selected EU countries, 2023. Source: author's elaboration based on [22,23]

As illustrated in Fig. 1, where countries are arranged in ascending order by the net earnings indicator, Bulgaria ranks among the lowest EV sales share countries, with only 4.8% in 2023, alongside Slovakia, the Czech Republic, Poland, and Croatia. At the same time, Bulgaria also has the lowest net earnings among all EU member states. This economic disparity contrasts sharply with the situation in Scandinavian countries, which boast high-income levels and EV market shares exceeding 33% in 2023, according to data from ACEA and Eurostat. Fig. 1 visually confirms the income gap

between Bulgaria and Scandinavian countries, which directly translates into EV adoption rates. Low net earnings levels directly influence the availability of charging infrastructure, a critical factor for EV adoption. According to ACEA data, Bulgaria is grouped with countries such as Croatia, Slovenia, Lithuania, Latvia, and Estonia, all of which are in the "red zone," which has the fewest charging stations across Europe.

This data is further illustrated in Fig. 2, where countries are arranged in ascending order by the number of charging points indicator. It highlights the clustering of low-infrastructure countries in the red zone, where Bulgaria is positioned. At the opposite end of the spectrum, just three countries account for 61% of all charging stations in Europe. The scarcity of charging stations creates a self-reinforcing cycle that hinders the growth of the EV market. Without external interventions or assistance, this vicious cycle perpetuates, preventing the creation of conditions necessary for EV adoption and growth.

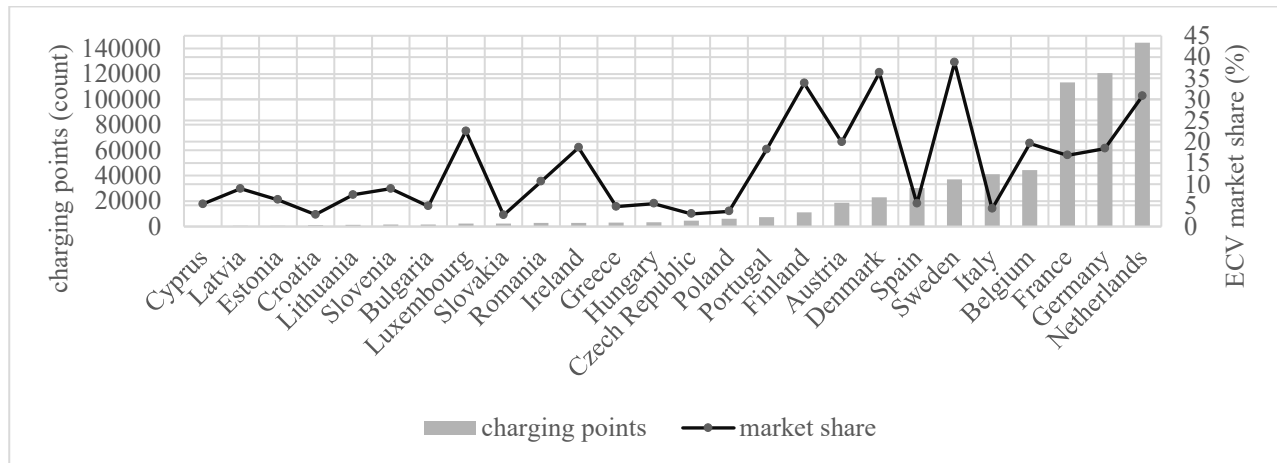


Fig. 2 ECV market share vs number of charging points in selected EU countries, 2023.

Source: author's elaboration based on [22,23]

As a result of the panel data analysis described in the data and methods section, the following equation is obtained:

$$MSEV = \alpha_i + \lambda t + 0.000589 * NCP + 0.4960 * GDP_PPS + 0.4854 * PD, \quad [-] \quad (3)$$

The study's empirical results are presented in Table 1.

Table 1 The empirical result of the panel data analysis. Source: authors

Variable	Coefficients β	Standard Error	t-statistic	P-value
NCP	0.0005894	0.00039164	1.5050	0.1465554
GDP_PPS	0.496***	0.12163326	4.0780	0.0004986
PD	0.485**	0.22145088	2.1919	0.0392639
TSS 39.559	RSS 21.947	R-Squared 0.44521	F-statistic: 5.88483	p-value: 0.0041525

Significance levels: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

The results indicate that the model is statistically significant at the 1% level, as shown by the F-statistic ($F = 5.88$, $p < 0.01$), suggesting that the included explanatory variables collectively explain variations in EV market share. The model explains 44.52% of the observed variation in EV market share. At the same time, the remaining variability reflects the complexity of EV adoption processes and the influence of additional institutional, policy-related, and behavioural factors not explicitly captured in the model. Economic development, proxied by GDP per capita in PPS, exhibits a substantial and statistically significant positive effect on EV market share at the 1% level ($\beta = 0.496$, $p = 0.0005$). A one-point increase in the GDP index is associated with an average increase of 0.496 percentage points in EV penetration, *ceteris paribus*. This result underscores the importance of affordability and purchasing power in the adoption of electric vehicles, particularly in lower-income countries. Population density also exhibits a positive and statistically significant effect at the 5% level, indicating that more densely populated and urbanised countries tend to experience higher EV adoption rates ($\beta = 0.485$, $p = 0.039$). A one-point increase in population density is associated with an average increase of 0.485 percentage points in EV penetration, *ceteris paribus*. This finding is consistent with shorter travel distances, higher urban mobility demand, and greater efficiency in deploying charging infrastructure in dense areas. Although the coefficient of public charging points is positive, it is not statistically significant in the baseline specification (0.000589, $p = 0.1465$). This suggests that, after controlling for country-specific characteristics and common time effects, the absolute number of charging points alone does not fully explain within-country changes in EV market share. This finding may reflect the fact that infrastructure expansion often follows, rather than precedes, EV adoption.

The Total Sum of Squares (TSS = 39.559) indicates substantial overall variability in EV market share across countries and over time, confirming that EV adoption is a heterogeneous process and providing a meaningful basis for regression analysis. The value of the Residual Sum of Squares (RSS = 21.947) indicates that approximately 55.5% of the variation in EV market share remains unexplained by the included variables, reflecting the fact that EV adoption is a complex process influenced by factors like additional state policy, institutional, technological, and behavioural factors that are not explicitly included in the current specification.

Overall, the results emphasise the dominant role of economic capacity and spatial structure in driving EV adoption in the examined countries, while highlighting that infrastructure availability plays a supportive but more nuanced role. These findings provide a solid empirical basis for the subsequent discussion of policy implications, with relevance for lower-income EU member states such as Bulgaria.

Meanwhile, in the fixed-effects framework, cross-country differences in EV adoption are captured by country-specific fixed effects, which reflect each country's persistent structural and

institutional characteristics. Countries with similar income levels and population density tend to exhibit comparable fixed effects, suggesting typical structural constraints and opportunities for EV adoption. They indicate whether a given country exhibits a structurally higher or lower EV market share after controlling for GDP, population density, charging infrastructure, and typical time effects. Countries with positive fixed effects exhibit higher EV market shares than predicted by economic development, population density, and infrastructure alone, while countries with adverse fixed effects face additional structural barriers. This heterogeneity suggests that the national context plays a crucial role in shaping EV adoption outcomes, extending beyond measurable economic and infrastructural factors. Figure 3 shows country fixed effects for the 6 CEECs from 2018 to 2023, with lower negative values indicating a more favourable structural environment for EV adoption after controlling for economic development, population density, and charging infrastructure. The results reveal considerable heterogeneity across the examined countries, even after controlling for economic development, population density, charging infrastructure, and typical time effects. Adverse fixed effects reflect relative deviations from the sample mean and should be interpreted in comparative, not in absolute, terms. The estimated fixed effects range from -112.69 for Czechia to -57.36 for Bulgaria, indicating substantial cross-country variation in EV market share that is not explained by the included covariates.

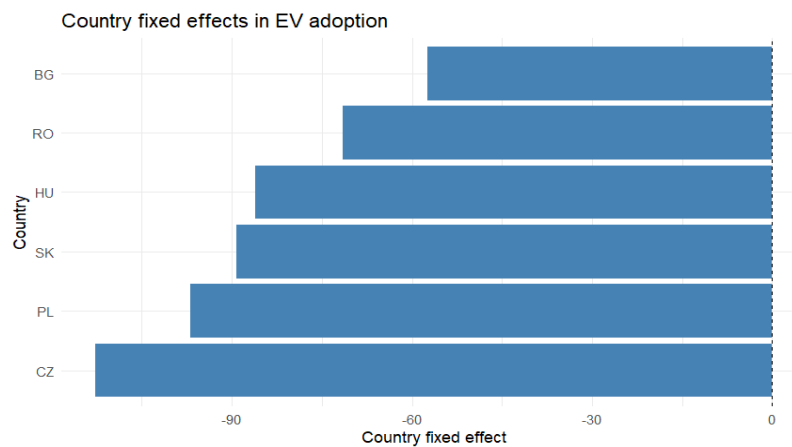


Fig. 3 Country fixed effects from the two-way fixed effects panel model in 6 CEECs 2018-2023. Source: author's elaboration

This means that EV adoption in Czechia is structurally lower than predicted by its economic and spatial characteristics. Meanwhile, despite its lower income levels, Bulgaria performs relatively better than several higher-income peers once observable factors are controlled for. Among the analysed countries, Bulgaria and Romania exhibit the least adverse fixed effects, while Czechia and Poland display the most negative values. Hungary and Slovakia occupy intermediate positions. These results highlight persistent cross-country differences in EV market penetration beyond observable economic and infrastructural determinants. The above-analysed model can be further enriched by incorporating

other significant variables and extending the dataset over additional years as more comprehensive statistics become available.

4. Discussion

The panel data analysis and the obtained results do not provide sufficient statistical evidence to support Hypothesis 1. Several factors may explain this finding. One plausible explanation is endogeneity, as the expansion of charging infrastructure may be a response to increasing EV adoption rather than its primary driver. Usually, the state finances investments driven by growing demand. Moreover, the impact of charging infrastructure may operate with some time lags that are not captured in the contemporaneous specification. It must also be considered that early-stage EV adoption may rely more heavily on private and workplace charging, reducing the immediate importance of public charging stations. In lower-income contexts, affordability constraints may play a more decisive role in shaping EV adoption, reducing the immediate influence of public charging availability.

The empirical results strongly support Hypothesis 2. The estimated coefficient for GDP per capita in PPS is positive and highly statistically significant, indicating that improvements in purchasing power substantially increase EV market share. This finding highlights the pivotal role of affordability in the adoption of electric vehicles, particularly in lower-income and later-adopting countries. In the context of CEECs, income constraints remain a fundamental barrier to EV adoption, suggesting that economic capacity is a prerequisite for the effectiveness of other policy measures. The dominance of income effects also helps explain why charging infrastructure alone does not exhibit a statistically significant impact, as infrastructure expansion is unlikely to translate into higher adoption without sufficient purchasing power. Higher income levels reduce the financial barriers associated with EVs' relatively high costs and facilitate access to financing. In more economically developed countries, access to credit is generally easier, and borrowing conditions tend to be more favourable. This is particularly important for the purchase of goods such as EVs, which have lower operating costs but require a relatively high upfront investment. Moreover, such countries typically exhibit higher levels of consumer environmental awareness, which translates into a greater willingness to adopt and invest in new technologies. In the context of CEECs, where income constraints remain pronounced, economic development emerges as a fundamental prerequisite for the diffusion of electric mobility.

The empirical results confirm Hypothesis 3. It is associated with shorter travel distances, making EVs more suitable for daily mobility needs. This reflects in decreasing the effect of range anxiety. At higher population densities, the economic efficiency of charging infrastructure increases, as a single charging station serves a larger number of users and is utilised more intensively. This enhances the impact of infrastructure even when the absolute number of charging stations is relatively low.

Moreover, in more highly urbanised environments, better access to home and workplace charging reduces reliance on public charging stations.

The country fixed effects indicate pronounced heterogeneity in EV adoption across the analysed countries, reflecting persistent structural and institutional differences beyond observable economic and infrastructural factors. Bulgaria and Romania exhibit relatively less adverse fixed effects, suggesting more favourable EV adoption outcomes given their income levels and population density. In contrast, Czechia and Poland exhibit stronger negative fixed effects, suggesting untapped potential and additional barriers to EV diffusion. These findings underscore the significance of national policy design, institutional effectiveness, and societal attitudes in influencing EV penetration.

5. Conclusion

Based on the analysis conducted, several key conclusions can be drawn. Replacing conventional vehicles with alternatives that meet the latest Euro standards is challenging and costly. Active state intervention is necessary at both the production and consumer levels. Without such support, the transition would be extremely slow and less effective in achieving the EU's goals. Tax instruments are particularly effective when they allow for exemptions from significant taxes. Otherwise, direct state support becomes crucial. Both approaches can be complemented with non-monetary incentives, such as access to bus lanes, designated zones, free parking, etc. In countries like Bulgaria, with low incomes, the lack of state support for electric vehicle adoption results in a small market share for alternative vehicles. Various economic and socio-demographic factors influence the purchase of electric vehicles. In Bulgaria and some CEECs, a positive relationship has been proven between the increasing market share of EVs and factors such as the GDP per capita and population density. Stimulating the electric vehicle market should be part of a comprehensive national policy that focuses on public investments in charging infrastructure, tax reliefs and subsidies for purchasing alternative vehicles, and awareness campaigns to educate the public about the benefits of electric vehicles. The main contribution of the paper is to provide empirical evidence on EV adoption in the specific context of an Eastern European country, such as Bulgaria. From a policy perspective, fiscal incentives are essential in the short term to increase affordability, while long-term success depends on investments in charging infrastructure and consumer awareness. Future research should expand the dataset, incorporate additional explanatory variables, and conduct comparative analyses with other countries in the region to deepen understanding of common challenges and effective policy solutions.

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