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Mobility at the crossroads – Electric mobility policy and charging infrastructure lessons from across Europe

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ABSTRACT

The transportation sector accounts for a significant part of European emissions and is one of the few sectors with rising emissions. Thus one crucial part of the European strategy to reduce overall emissions is a shift, in the transportation sector, to low-emission mobility and electric mobility in particular. As European governments and policymakers consider feasible ways of supporting the transition, one central question is whether the policies and actions they enact should aim for creating incremental or structural change, here operationalized as personal incentives vs. charging infrastructure. Therefore, this analysis investigates the effects of electric mobility policies and charging infrastructure on plug-in electric vehicle (PEV) market shares in Europe from 2009 to 2019. Charging infrastructure, and fast charging infrastructure in particular, demonstrate by far the strongest and most robust results of the analysis, having a significant positive effect on PEV market shares in all models. The analysis also suggests that purchase incentives, ownership tax benefits, and the policy packages for electric mobility tested have a positive and significant effect on PEV adoption. However, these effects are notably weaker and exhibit far less robust findings across the models in the analysis. Thus, while the study cannot conclusively come down on the side of infrastructure over personal incentives, it persuasively points to the crucial importance of charging infrastructures for the electrification of transportation. Theoretically, this makes sense—personal incentives will increase the market shares of PEV, but only incrementally, running the risk of merely supplementing the old fossil fuel-based transportation system rather than replacing it. Charging infrastructure on the other hand creates the potential for structural change, implying that a more active and coordinated build-out of charging infrastructure is needed to ensure a rapid transition to low-emission mobility.

1. Introduction

Worldwide, the transportation sector accounts for around ¼ of greenhouse gas emissions and is one of the few sectors that continues to increase its emissions. In the EU28 countries in 2017, 25% of emissions came from transportation (including international aviation), which is a 10% increase from 1990 levels, and passenger cars alone account for 12% of the EU's total CO_2 emissions (European Commission, 2020). Member countries have adopted the European Commission's strategic vision of an irreversible shift to low-emission mobility through several regulations and directives (European Commission, 2009, 2013; 2014; 2017). EU member countries have signed up to the 2030 target of 40% greenhouse gas emission cuts by 2030 from 1990 levels (European Commission, 2018), a target which members have now agreed to increase to 55% by 2030, as part of the new European Green Deal proposal (European

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Commission, 2021).

A shift toward a cleaner and more efficient transportation system has several additional benefits such as less air and noise pollution, and less fossil fuel import dependency for Europe (Biresselioglu et al., 2018). What is less clear, and difficult to predict, is how Europe and the rest of the world will get there. Great transitions, and the energy transition in particular, are the subject of great debate and scholarly interest. Their length, reach, and impact on society and the natural world have been studied in great detail (e.g. Smil, 2010, 2017), although to a lesser extent by social scientists (one exception is: Sovacool, 2016). Given its importance, the energy sector has been the centerpiece of much of this literature while research on the transportation sector has, at least comparatively in relation to its emission share, been vastly understudied until quite recently. The rate of change in the energy sector has been incredible and energy-related emissions are decreasing fast due to the rapid uptake of ever cheaper renewable energy sources like wind and solar photovoltaics. However, the International Energy Agency (IEA) (2019) estimates that transport-related emissions, at 32% of total final energy consumption, were almost twice as large as energy sector emissions (17%) in 2018. Yet most of the focus has been on the energy sector.

From the transition literature, there is an emphasis on structural change and much of the debate around transitions and structural change evolves around its pace and their drivers. Do energy transitions move gradually, incrementally and seamlessly toward a new paradigm as new technologies become better and cheaper than old and obsolete ones, or do they happen as a result of abrupt shocks or by disruptions through a process more akin to Schumpeter's (1942) waves of creative destruction? Finally, what role do states, institutions, and vested interests play in these structural changes (Moe, 2010; 2015; Patt, 2015)? Or is our transportation system mired in what Unruh (2000) calls a "techno-institutional complex", where strong fossil fuel and legacy automobile companies have created powerful feedback loops between the technological infrastructure and institutions, thereby forging lock-ins that are difficult to displace? While it has been more common to talk about such a complex in the energy sector, in many ways it is even more reasonable to assume that something resembling a techno-institutional complex is present in the transport sector. With only 0.3% of final energy consumption for all transport coming from renewable electricity and a mere 3% from biofuel (which is by no means unproblematic) (REN21, 2020 p.33), and containing some of the world's largest companies, both car manufacturers and oil companies (Fortune, 2020), the existence of a transport techno-institutional complex is more than plausible. With this in mind, one central cleavage within transportation sector policy revolves around the divide between infrastructure and personal incentives. On one side, there are the economic-centered notions of pricing externalities, price signals, and tax exemptions. Here, financial incentives, deductibles, and exemptions create favorable market conditions for consumers waiting to purchase a cleaner vehicle. Levying increased taxes on vehicles with an internal combustion engine or increased taxes on fossil fuel at the gas pump perform analogous disincentives to running a fossil fuel-based one. The underlying notion is that by simply getting the "price right" or making the "polluter pay" the informed consumer will opt for the cleaner option (Hardman et al., 2017). Eventually, electric cars will replace gasoline ones simply because they are better and cheaper.

However, the fact that emissions from the transportation sector are still rising (IPCC, 2014; IEA, 2021), lends credence to an alternative view that says policymakers cannot sit idly by while market forces incrementally move us toward low-emission vehicles. The argument here is that the assumption that getting the price right and making polluters pay will inevitably lead to structural change is at best grossly simplified, and at worst downright wrong. Incremental change does not necessarily lead to structural change; it follows a very different logic. Thus, these transitions do not just happen by themselves and personal economic incentives will only get us so far. Instead, these transitions require the state and institutions to play an active role in coordinating and facilitating changes in areas where markets act too slowly, or are even incapable of acting, such as in infrastructure. In sum, this view advocates that structural change in these contexts implies building infrastructure and systems that replace, rather than incrementally supplement, the old fossil fuel-based transportation system.

This study represents a comprehensive empirical analysis of the effects of electric mobility policy, charging infrastructure on the share of plug-in electric vehicles (PEV) of total passenger car sales in 32 European countries from 2009 to 2019. The analysis is based on a new state-of-the-art dataset manually collected, formatted and sorted from several sources, including the European Alternative Fuels Observatory (EAFO), the OECD.stat Database, Eurostat, and the World Bank Open Data, and then constructed for panel data analysis on electric mobility. Increasing amounts of literature have been devoted to studying the effect of traditional electric vehicle incentives and by what means governments can increase PEV adoption among its citizens. A large state-of-the-art literature review, conducted by ECHOES—a Horizon2020 project this author between 2017 and 2019 was part of—found that the vast majority of studies on electric mobility were focused on the national level, clearly suggesting a lack of international and large sample regional country studies for electric mobility. Most of these studies have focused on one or a few specific, usually large, countries, such as Germany and the UK, or success stories like Norway, which is famous for its very generous PEV policies (Biresselioglu et al., 2017; Biresselioglu et al., 2020). This study, therefore, improves and ameliorates the lack of literature on more extensive regional cross-country studies, focusing on Europe. Large sample empirical studies such as this one should complement case studies and smaller comparative studies (e.g. Nordic country comparative studies) because they provide overarching analysis of trends and effects that are not captured by case studies, simply because they are too case or national specific. Another argument is that the few countries that are most studied are rich, developed countries with evolved PEV markets, while this sample is non-discriminatory with regard to GDP or other measures. To date, to my knowledge, only two papers have conducted a systematic large-scale cross-country study of factors affecting PEV sales; Sierzchula, Bakker et al. (2014) looking at 30 countries spread across the world in a single year, 2012, and Münzel et al. (2019) who looked at financial incentives and PEV adoption in 32 European countries from 2010 to 2017. By contrast, this empirical analysis spans 2009 to 2019, covering 32 European countries in one analysis and looks at both charging infrastructure and personal incentives.

The paper is organized in the following order: Section 1.1 presents a brief overview of definitions and trends in electric mobility in

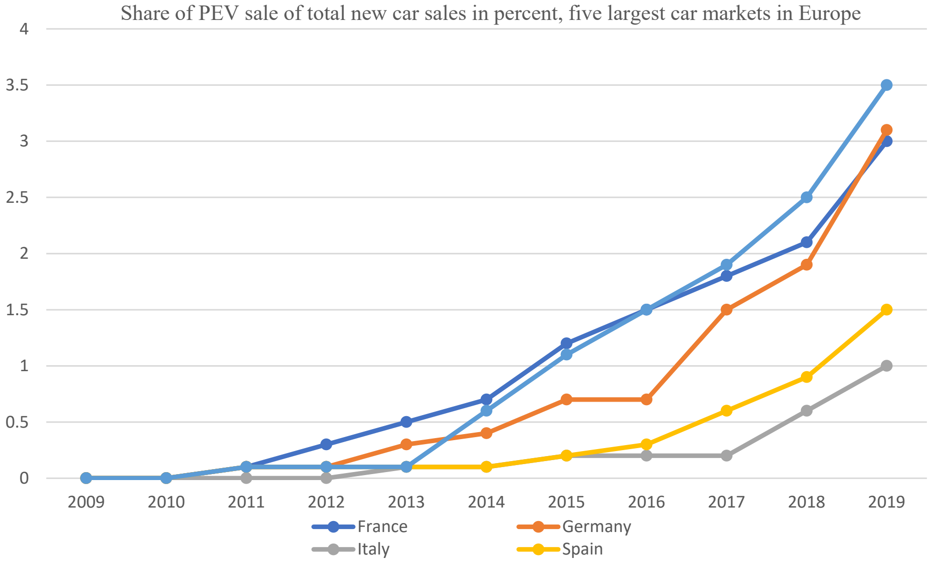

Fig. 1. Plug-in electric sales in selected European markets (share of total new car sales from 2009 to 2019). Source: European Alternative Fuels Observatory (EAFO).

Europe, followed by Section 2, with a summary of relevant literature on electric mobility policy and charging infrastructure. Section 3.1 presents the dataset and variables, with Section 3.2 following up with the model specification. Results and a discussion of these are presented in Section 4, followed by conclusions and policy implications in Section 5.

1.1. *Electric mobility terminology, developments and trends in Europe*

EU regulation uses the term zero- and low-emission vehicles (ZLEV), where a ZLEV is defined as a passenger car or van with CO_2 emissions of between 0 and 50 g/km (European Commission, 2019). Appendix Table A1 thus shows that most modern plug-in hybrid models in fact comply with the EU regulation limits today[1]. Other common terms for these types of vehicle are battery electric vehicle (BEV), or all-electric vehicle, one that gets all its power from its onboard battery pack, and plug-in hybrid vehicle (PHEV), that contains both an electric motor and an internal combustion engine together with a plug to connect it to the grid for charging (EAFO, 2020a,b). Following this, a plug-in electric vehicle (PEV) is a classification that includes both BEVs and PHEVs (Hardman et al., 2017). Since EAFO (PEV) and EU Regulation (ZLEV) classifications have considerable overlap, the following analysis will adopt the term plug-in electric vehicles (PEV). Vehicles with an internal combustion engine will be referred to as internal combustion engine vehicles (ICEV). The benefits of vehicles with battery technologies is first and foremost lower emissions and pure battery-electric vehicles have no tailpipe emissions, which contributes to lower climate emissions and air pollution and less noise. An electric engine is also far more efficient than an internal combustion engine (IEA, 2020), so the energy consumption is smaller. Anecdotal evidence from Norway, which has the highest share of PEV in the world, at over 50% in 2020, shows that the electricity consumption from charging has so far been marginal. The Norwegian electricity supplier, Statkraft, has calculated that the consumption of charging all PEVs in Norway was just 703 GWh in 2020, a mere 0.53% of total Norwegian electricity generation, at 153.3 TWh (TU, 2021). Looking at battery production and cost development, the picture is even more optimistic. A recent paper by Ziegler and Trancik (2021) finds estimated annual cost declines of 13% for lithium-ion cells from 1992 to 2016, constituting a 97% cost decline since its commercial introduction in 1991, and 20% cost declines for all cell types and 24% for cylindrical cells for every doubling of the cumulative market. The declining battery costs and other improvements indicate that PEVs will start to approach price parity with ICEVs (see for instance: Nykvist et al., 2019; UBS, 2019; DNV GL, 2020; BNEF, 2020; EVO, 2020a,b; IEA, 2020; Lander et al., 2021).

Fig. 1 shows that several key European markets have seen slow adaption rates, but that sales are growing, and this is generally true in all European countries. The COVID-19 pandemic caused significant drops in all new car sales through 2020, although PEV car sales held up better than new ICEV sales and have seen its overall market share rise considerably in all European markets (EVO, 2020a,b).

2. Literature review and hypotheses

Research on PEV adoption and uptake can be divided roughly into four main categories; (1. fiscal or economic factors, e.g., purchase price, taxes, fees, and the total cost of ownership. (2. technological factors, such as range, charging time, charging networks and

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[1] CO_2 emissions as gram/km based on NEDC standard. The NEDC standard has now been replaced with the WLTP standard which aims to represent real and modern driving conditions more accurately.

infrastructure, (3. local policies or incentives, such as free toll crossings, free parking, access to bus lanes, and finally, (4. individual or behavioral factors, such as identity, environmental consciousness, customer awareness. The other massive literature relevant for the electrification and decarbonization of transport is the batch on total life cycle emissions, material use, and costs of PEVs. Here, topics such as life-cycle analysis (LCA), analysis of various stages of “well-to-wheel”[2] and integrated energy models (IEMs) are discussed, covering topics surrounding national and global energy and electricity mixes, emissions, and critical materials use. In this literature review, I mainly focus on the first two, i.e. primarily economic and infrastructural factors, or to put it differently, personal incentives versus infrastructure, which represent deeper theoretical discussions in the literature on energy transitions—namely, incremental versus structural change.

Legitimate concerns over mass PEV adoptions tend to focus on the vehicle’s life cycle assessment, with secondary questions related to the electricity mix used to both produce the batteries and the vehicle and the mix that charge the vehicle. The potential of increased pressure on national grids caused by mass PEV adoption, especially in nations and regions that lack sufficient grid infrastructure is another issue of concern. Countries are on different development paths and we should be reminded of this point when applying broad generalizations and policy recommendations. For instance, Onn et al. (2018) find that a massive uptick in electric vehicle charging would, in fact, increase greenhouse gas emissions due to its fossil fuel-dependent grid infrastructure. However, while not all countries and regions have the capacity and financing to decarbonize their power sector rapidly, it is generally agreed that to reach the Paris climate agreement goals, the world needs to decarbonize both the transportation sector and the energy system as fast as possible. The promise of cost reductions, innovation, and technological development can alleviate some of these problems, and promising developments, such as vehicle-to-grid (V2G) technologies, while no panacea, show that additional CO_2 reductions can be achieved vis-à-vis simply replacing ICEVs with PEVs (Tomić and Kempton, 2007; Xu et al., 2020) as well as performing valuable grid management responses (see for instance: Guille and Gross, 2009; Tan et al., 2016; Garcia et al., 2018; Alirezazadeh et al., 2021).

Reports comparing electric vehicles and PEVs with ICEVs are becoming commonplace. While not all efforts have the scientific rigor one might expect, more or less every serious analysis finds electric vehicles to be more climate-friendly than their fossil-fuel counterparts, even if charged by fossil-heavy grids (see for instance: Hoekstra, 2019; Knobloch et al., 2020), and as grids decarbonize, the environmental impact decreases rapidly (see for instance Burchart-Korol et al. (2020) for LCA analysis of EV charging in European countries toward 2050). LCA analyses by Ellingsen et al. (2014) and Ellingsen et al. (2017) also find considerable emissions savings from electric vehicles, even with the manufacturing process taken into account. Material use and efficiency are also topics of considerable research, and several studies have looked at the effect of material use, ranging from increased use of lighter materials and improved recyclability (see for instance: Hottle et al., 2017; Hertwich et al., 2019; Milovanoff et al., 2019).

Another approach that concerns the energy use and greenhouse gas emissions from automotive fuels and powertrain options is well-to-wheels (WTW) analysis. The main aim of WTW is to investigate and usually compare fuels and vehicle options, in other words looking at the ‘in-use’ emissions. WTW thus differs from LCA as it does not usually include emissions and energy expended in the manufacturing of the vehicle or end-of-life aspects (EU, 2016). There is also a range of stages researchers can investigate, such as well-to-station, station-to-tank, and tank-to-wheel. In the literature, there is a well-known dilemma around whether energy production should be considered throughout its lifespan, i.e., from well-to-wheel or only during the last phase of the process; tank-to-wheel. This is because the same vehicle using the same amount of energy in two different countries may have significantly different environmental impacts due to the differences in the national and local production and transport of energy. Cavallaro et al. (2018) use WTW analysis of BEVs and non-BEVs at the European level and find large variations across European countries and segments. They point out that we should distinguish according to vehicle classes (e.g., comparing small BEVs with smaller ICEVs) and country profiles. However, they still venture some general conclusions and assert that, firstly, ICEVs emit more carbon than other vehicles in all European countries in the study. Secondly, as the energy mix is the crucial determinant for establishing the carbon efficiency of alternative fuel vehicles, the authors find that PHEVs produce less carbon than BEVs in countries with a high amount of fossil fuels in their energy mix (e.g., a large share of coal), especially for vehicles characterized by high fuel/energy consumption such as SUVs. Kosai et al. (2018) find that including material structures in the manufacturing phase and fuel consumption at the operation phase leads to significantly higher WTW emissions estimations. The authors state that the inclusion of the energy consumption for the material structure (e.g., from the battery) has considerable impacts on the vehicle energy efficiency, especially for the new generation of vehicles (e.g., PEVs). The results suggest that as energy production and the energy used in battery production are cleaned up, significant improvements of battery-electric and hybrid powertrain options should become apparent.

Another common method to explore pathways for transportation is integrated energy models (IEMs). Wolfram and Hertwich (2019) investigate assumptions in 14 state-of-the-art integrated energy models for light-duty vehicles (LDV) and show that decarbonization efforts in the LDV sector might be more cost-effective than previous estimates. For instance, updating cost estimates for electric vehicle batteries in line with current technological development would more accurately represent mitigation scenarios, which again has considerable implications for policymakers using IEM output to guide climate policy action.

The bottom line for most of these studies is that the electrification of vehicles, while not a perfect solution, is better for the climate than fossil fuel-based vehicles and will continue to be so as Europe adds more renewable energy to its electricity mixes. Technological developments and efficiencies will presumably also lower the footprint of both manufacturing and battery production, both of which will benefit tremendously from being produced with electricity from ever cleaner sources (Märtz et al., 2021). Another key takeaway is that while PEVs (and especially BEVs) can progressively become less emission-intensive over time as the European grids charging them

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[2] The stages of “Well-to-wheel” (WTW) are “well-to-tank” (WTT) and “tank-to-wheel” (TTW) (see for instance: EU, 2016).

are gradually decarbonized, the same cannot be said for an ICEV. One should, therefore, arguably think more dynamically rather than statically about these questions. With the EU proposing its new European Green Deal, thereby raising greenhouse gas emission reduction ambitions from 40% to 55% in 2030, we can expect increased efforts in deploying more renewable energy, increased promotion of PEVs, and an increased focus on the European battery supply chain.

With this backdrop, where this article contributes to the literature is in investigating the effects of PEV policies and charging infrastructure. Economic incentives and other market-based policies, such as purchase incentives, tax and VAT deductions or exemptions, and general reductions in fees and taxes of ownership are the subject of many studies over the last decade, and most of these suggest more or less that financial incentives do work (Sierzchula et al., 2014; Aasness and Odeck, 2015; Zhou et al., 2015; Rudolph, 2016; Zhou et al., 2016; Slowik and Lutsey, 2016; Kester et al., 2018; Fluchs, 2020; Gong et al., 2020). Hardman et al. (2017) systematically reviewed the effectiveness of financial incentives for BEV and PHEV promotion and found that 1) incentives should be applied at the point of the sale, not afterward, 2) incentive schemes should differentiate between low and high-end BEVs and long and short ranged PHEVs. Low-end BEVs should receive larger incentives than high-end BEVs and longer range PHEVs should get similar incentives to low-end BEVs. Finally, short ranged PHEVs should receive the smallest incentives due to their small batteries with resulting low electric driving range. Finally, 3) they find that VAT and purchase tax exemptions are most effective. The authors also raise the point that premature removal or uncertainty surrounding the policy could negatively affect PEV sales, and therefore policymakers need to design incentive structures with longevity in mind. Sierzchula et al. (2014), Mock and Yang (2014), Mersky et al., 2016, and Axsen et al. (2020) also find significant positive effects of financial incentives on PEV adoptions, while all studies clearly underline the importance of policy mixes and conclude that financial incentives alone are not enough to increase PEV adoptions significantly. These results are confirmed by Münzel et al. (2019) in one of the few empirical studies outside the US. Finally, Gallagher and Muehlegger (2011) found that rising fuel prices were associated with higher PHEV sales in the US, while they could not find any relationship between consumers' income and education.

The literature has, to a lesser extent, investigated the effects of infrastructure for the transition to low-emission mobility, but evidence is building for the importance of charging infrastructure for PEV adoption (see for instance: Lieven, 2015; Javid and Nejat, 2017; Kester et al., 2018; Wei et al., 2021). Additionally, beyond confirming the significant effect of financial incentives, Sierzchula et al. (2014) find that charging infrastructures were a significant factor for electric vehicle adoption. The model results suggest that the charging infrastructure effect was even more substantial than the effect of financial incentives. Further research by Bakker and Trip (2013) suggests that the build-up of charging infrastructure is a key enabler for PEV adoption rates and rests on favorable and consistent governmental support and regulation, emphasizing the role of private–public partnerships as one favorable route to go. A recent study by Haustein et al., (2021) also finds that new fast-charging increased BEV adoption in Denmark, and although no such effect in Sweden was observed, still suggests that better infrastructure and clear policy signals, as well as marketing tailored explicitly for electric mobility, can increase the adoption of BEVs. Contrastingly, Miele et al. (2020) only find limited effects of additional charging and refueling infrastructure in their simulation of zero-emission vehicle sales in Canada to 2030. The simulation suggests that other strong policies are needed to stimulate sales of zero-emission vehicles. Funke et al. (2019) find that public charging infrastructure is still a barrier to PEV adoption, especially where home charging is not possible, such as in some densely populated areas, but highlight that framework conditions vary significantly from country to county. So it is hard to determine the optimal level of public charging infrastructure that applies to all countries. Considering that Hardman et al. (2018) find that between 50 and 80% of charging happens at home, with the workplace as the second most common charging place, and that public charging, both fast and slow only accounts for <10%, it makes it important to pose questions about the levels of charging infrastructure needed. Meunier and Ponssard (2020) find that optimal BEV policy includes both subsidies for both the build-out of charging networks and the BEV, while Greaker (2021) finds that direct subsidies for BEVs can be superfluous if both charging of BEVs and entry costs of charging stations are subsidized. Greaker highlight that this result relies on several conditions that are rarely present in real-world markets today, such as sufficient pricing of the environmental impact of ICE vehicles, which suggest that some form of incentives for BEV purchases should be in place.

Anecdotal evidence from Norway suggests that once a country reaches a certain market share of PEV, the existence of an adequate charging infrastructure with sufficient charging speeds and the inconvenience of long charging queues along highway corridors are issues that are taking over from the more classic one of range anxiety (TØI, 2019). As deep-rooted industrial lock-ins and vested interests make transitions slower, innovation and technological development are also regarded as essential transition-enablers as technical and economic hurdles are overcome, thereby making economic rationale of purchasing a PEV more appealing to more consumers (see for instance: Newell, 2009; Patt, 2015; Mazzucato, 2015). Finally, Fritz (2019) find that ambitious fuel standards are a powerful instrument for CO_2 emission reduction and PEV market diffusion. Interestingly, they find that current fuel standards are lower than the automaker's own targets when their PEV targets are taken into account.

Through a structural change lens, the interesting question is not how to get to 10% market share, but how a structural change to low-emission mobility happens—i.e., how to get to 50% and higher PEV market shares—and it is doubtful that this will happen through personal incentives alone. The story of incremental change can quickly lead to a plateau in market shares simply because the surrounding transportation system has not coordinated and transformed sufficiently to accommodate the changes. The story of structural change then, clearly advocates building infrastructure and systems that replace, rather than just supplement, the current transportation system.

As a final note, there is a lot of literature on psychological and behavioral factors at the individual level connected to the energy transition in general and within electric mobility and PEV adoption specifically. The literature on this looks at factors such as information about the new technology and user acceptance of it (see for instance: Graham-Rowe et al., 2012; Plötz et al., 2017; Plötz and Dütschke, 2020), trust in PEVs' environmental friendliness, social desirability and symbolism among other factors (e.g., Axsen and Sovacool, 2019; Long et al., 2019). And while it is outside of the scope of this article, it is nevertheless recognized as a crucial research

Table 1
Summary statistics: PEV indicators, charging variables and control variables.

Variables	N	Mean	St.dev	Min	Max
Share of PEV of total new registrations (*logged)*	352	0.48	0.71	0	4.04
Share of BEV of total new registrations (*logged)*[*]	352	0.34	0.55	0	3.77
Normal public charging points per capita (*logged*)	352	1.42	1.50	0	5.66
Fast public charging points per 100 km highway (*logged*)	352	1.28	1.52	0	6.49
GDP per capita (*logged*)	352	10.29	0.67	8.81	11.62
Urban population	352	73.91	12.48	52.43	98.04
Residential electricity price	352	0.17	0.05	0.08	0.31
Pump price petrol and diesel	352	2.12	0.80	0.99	5.88
Share of renewable energy of total generation[**]	296	34.47	25.75	0.59	99.99

[*] Used in the robustness model.
[**] Used in the instrumental variable (iv) regression model to test reverse causality.

area in order to understand motivations and challenges for the energy transition.

Summed up, based on the literature, I propose the following hypotheses to be tested empirically:

H1. (*PEV incentives and electric mobility policies*) The market share of PEV is higher in those market with more electric mobility incentives and policies.

H2. (*Electric mobility packages*) The market share of PEV is higher in those market which have introduced policy packages of electric mobility incentives and policies.

H3. (*Charging infrastructure*) An increase in charging infrastructure has contributed to an increase in PEV market share of new car registrations.

H4. (*Fast charging infrastructure*) An increase in fast-charging infrastructure has contributed to an increase in PEV market share of new car registrations.

3. Data and methodological approach

3.1. Data and variables

The dataset used in this analysis has been collected, formatted, and sorted manually by the author and provides unique, updated and state-of-the art data for electric mobility data analysis (Sæther, 2022). The analysis investigates an 11-year period from 2009 to 2019. The raw data is obtained primarily from the European Alternative Fuels Observatory (EAFO), a database and online portal funded by the European Commission in order to support member states' implementation of EU Directive 2014/94 on the deployment of alternative fuels infrastructure (European Commission, 2014). In addition, several variables are obtained from the OECD.Stat Database, Eurostat and the World Bank Open Data database. The dataset covers 33 European countries, including Turkey, while the analysis excludes Lichtenstein[3]. Summary statistics for the variables are shown in Table 1.

Data for the PEV market share of new registrations of total car sales—all categories (*Share of PEV of total new registrations*) and the BEV market share of new registrations of total car sales—all categories (*Share of BEV of total new registrations*), which is used for robustness testing—are both collected from EAFO (EAFO, 2020a) and are defined as newly registered passenger vehicle category M1; used for the carriage of passengers, with no more than eight seats in addition to the driver's seat, also known as passengers cars, following UNECE standards (EAFO, 2020b). Both variables are logarithmically transformed as both are heavily skewed and have high kurtosis.

Two variables for electric mobility infrastructure are included in the analysis. The first measures normal public charging points ($<=$ 22 kW) per capita (per 100.000) (*Normal charging points per capita (logged)*) and is calculated by dividing the number of normal public charging points by total population in a given year and multiplied by 100.000. The second variable for fast charging infrastructure (*Fast public charging points (logged)*) is defined as fast ($>$22 kW) public charging points per 100 km of highway. Charging infrastructure is here defined as public chargers that have 'non-discriminatory' access, but also includes chargers that are sometimes referred to as "semi-public" chargers, such as public chargers at supermarkets or parking lots. Data on both charging variables are obtained from the EAFO database (EAFO, 2020a) and both are logarithmically transformed in the analysis.

In order to test the effect of various low-emission mobility incentives, I have constructed several dichotomous variables. In addition, I test bundles of policy incentive packages to investigate the effect of sets of multiple incentives (i.e. purchase subsidies and ownership benefits) versus single policies, shown in Table 2. The dichotomous variables are operationalized as 0 = the country does not have the incentive in a given year, and 1 = the country has the incentive in a given year. Data for all low-emission mobility incentives are collected from the EAFO database (EAFO, 2020a) and cross-referenced from country-by-country official and semi-official

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[3] Lichtenstein lacks data on several key variables and is thus excluded from the analysis.

Table 2
Summary statistics: Low emission mobility policies.

Variables	N	Min	Max	N = 0	N = 1
Purchase incentives (*Pi*)	352	0	1	233	119
Purchase subsidies (*Ps*)	352	0	1	256	96
Registration tax benefits (*Rtb*)	352	0	1	227	125
Ownership tax benefits (*Otb*)	352	0	1	212	140
Company tax benefits (*Ctb*)	352	0	1	253	99
VAT benefits (*VATb*)	352	0	1	324	28
Local incentives (*Li*)	352	0	1	284	68
Policy package 1	352	0	1	323	29
Policy package 2	352	0	1	286	66
Policy package 3	352	0	1	317	35
Policy package 4	352	0	1	287	65

sources[4]. Purchase subsidies (*Purchase subsidies, Ps*) are classified as a state subsidy that is granted to a private customer, and/or businesses and/or municipalities for the purchase of a PEV. VAT benefits (*VAT benefits, Vb*) covers lower rates or exemptions from value added taxes. Following the classification of Hardman et al. (2017), *purchase subsidies* and *VAT benefits* have been combined to create the variable purchase incentives (*Purchase incentives, Pi)*. Tax reduction or exemption for registration taxes (*Registration tax benefits, Rtb*) is classified as exemption or significant reduction in taxes or fees related to registration of a PEV. Ownership benefits (*Ownership tax benefits, Otb*) are defined as benefits such as exemption or significant reduction of annual circulation/road taxes and other federal taxes related to ownership of a vehicle. Company benefits (*Company tax benefits, Ctb*) are operationalized as benefits such as deduction on company taxes for PEVs operating as company car. And finally, local incentives (*Local incentives, Li*) are defined as free or beneficial parking, exemptions or significant reductions for toll crossing, and permission to use bus lanes.

In addition, I test several policy packages; Policy incentive package 1 (*Policy package 1* ($Pi + Rtb + Otb + Ctb + Li$)) covers a package of incentive policies that includes all incentives tested. Policy incentive package 2 (*Policy package 2* ($Pi + Rtb + Otb$)) covers incentives related to purchase and ownership costs. Policy incentive package 3 (*Policy package 3* ($Pi + Rtb + Otb + Li$)) covers incentives related to purchase and ownership costs, as well as any local incentives. Lastly, policy incentive package 4 (*Policy package 4* ($Pi + Ctb$)) covers the incentives aimed at private and company purchases, where there is some overlap. In order to be coded as 1, the country has to have had all incentives in the policy package in a given year.

The indicators measuring urban population (*Urban population*), measuring the percentage of the total population that lives in urban areas as defined by national statistical offices, and GDP per capita (*GDP per capita (logged)*), measuring GDP per capita, where gross domestic product divided by mid-year population in constant 2010 US dollars are both obtained through the World Bank Open Data database (2020a, 2020b) and the variable has been logarithmically transformed in the analysis. Residential electricity prices (*Residential electricity prices*) are measured in Euro per kWh and have been collected from Eurostat (Eurostat, 2020) with data on Switzerland collected from The Swiss Federal Office of Energy (SFOE, 2020). Finally, to estimate an indicator for the fuel costs of ICEVs, two indicators of the fuel user price of petrol and diesel in 2010 US dollars per liter are combined into variable measuring the mean pump price for fuel (*Mean pump price petrol and diesel)* and have been collected from the OECD Green Growth database (OECD.stat, 2020).

3.2. Model specifications

Panel data or time-series cross-sectional data suffer from two main problems that need to be controlled for. The first is temporal dependence, or autocorrelation, where the error term correlates across the panel over time and can inflate the standard errors thus leading to biased results. The second problem is spatial dependence or cross-sectional dependence. Here, the units, in this case the countries, correlate systematically with each other across space. Both problems need to be controlled for in order to produce unbiased estimates. Therefore, this study deploys panel data regression with the fixed-effects estimator with Driscoll-Kraay standard errors to investigate the effects of electric mobility incentives and charging infrastructure on the share of PEV registrations. Using the fixed-effects estimator, equivalent to the unit centering all observation, we can investigate deviations in the mean in each unit over time (Petersen, 2004). Fixed-effect models only estimate within-country variation, making comparison between countries impossible. Moreover, a fixed effects model does not allow for time-invariant variables in the analysis (Petersen, 2004; Beck, 2008). The Driscoll-Kraay method estimates standard errors that are robust to spatial correlation and heteroscedasticity using ordinary least squares (OLS) regression (Driscoll and Kraay, 1998; Hoechle, 2007). The analysis also deploys temporal control by adding year dummies as time fixed-effects in all models.

In this study we are interested in whether or not increases in charging infrastructures significantly increase PEV shares and whether or not implementation of electric mobility incentives and packages of incentives yield significant increases in PEV shares of new car registrations. And secondly, if significant, can we say something about the size of their contributions relative to each other? Finally, in order to test reverse causality for the charging infrastructure indicators I employ an instrumental variable regression model based on Baum et al. (2007). The iv-regression model runs share of renewable energy of total electricity generation as the instrumental variable.

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[4] National electric mobility organizations etc.

Table 3
Effects of charging infrastructure and electric mobility policies on PEV market share of new registrations in Europe.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Share of PEV	Share of PEV	Share of PEV	Share of PEV	Share of PEV	Share of PEV
Normal charging points per capita (*logged*)	−0.172***	−0.178**	−0.173***	−0.173***	−0.186***	−0.177***
	(0.0502)	(0.0614)	(0.0534)	(0.0514)	(0.0547)	(0.0549)
Normal charging points per capita (*squared*)	0.0606***	0.0585**	0.0597***	0.0589***	0.0622***	0.0574**
	(0.0172)	(0.0211)	(0.0179)	(0.0185)	(0.0183)	(0.0187)
Fast public charging points (*logged*)	0.260***	0.271***	0.263***	0.266***	0.257***	0.266***
	(0.0198)	(0.0217)	(0.0189)	(0.0188)	(0.0192)	(0.0194)
Purchase incentives (*pi*)		0.142*				
		(0.0716)				
Registration tax benefits (*Rtb*)		−0.0193				
		(0.0323)				
Ownership tax benefits (*otb*)		0.111**				
		(0.0491)				
Local incentives (*li*)		−0.0385				
		(0.112)				
Policy package 1			0.204*			
			(0.112)			
Policy package 2				0.253***		
				(0.0513)		
Policy package 3					0.347***	
					(0.108)	
Policy package 4						0.149**
						(0.0579)
Urban population	0.0599***	0.0674***	0.0504***	0.0667***	0.0436***	0.0578***
	(0.00879)	(0.0183)	(0.0111)	(0.0135)	(0.0117)	(0.00943)
GDP per capita (*logged*)	−0.432*	−0.350	−0.586**	−0.614**	−0.678***	−0.482*
	(0.228)	(0.235)	(0.185)	(0.233)	(0.196)	(0.233)
Residential electricity price	−0.750	−1.154	−0.948	−1.633	−1.346	−1.170
	(1.073)	(1.032)	(1.121)	(1.130)	(1.125)	(0.944)
Mean pump price petrol & diesel	0.248*	0.298*	0.228*	0.248*	0.205	0.238*
	(0.132)	(0.173)	(0.126)	(0.141)	(0.128)	(0.133)
Constant	−0.304	−1.737	2.019	1.173	3.555	0.437
	(2.733)	(3.488)	(2.156)	(3.006)	(2.218)	(2.802)
Observations	352	352	352	352	352	352
Number of countries	32	32	32	32	32	32
Time FE	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

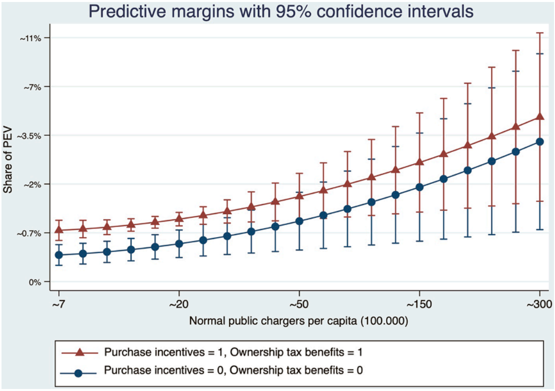

Fig. 2. Predicted PEV market share of new registrations with an increase in normal public chargers per capita (100.000) with or without a purchase incentives and ownership tax benefits.

4. Results and discussion

Table 3 presents the regression results for the fixed-effect models. Table 3 shows the results for PEV market share of new registrations, while Tables A2, A3, A4 and A5 show the robustness test estimates. All tables report the estimated coefficients and Driscoll-

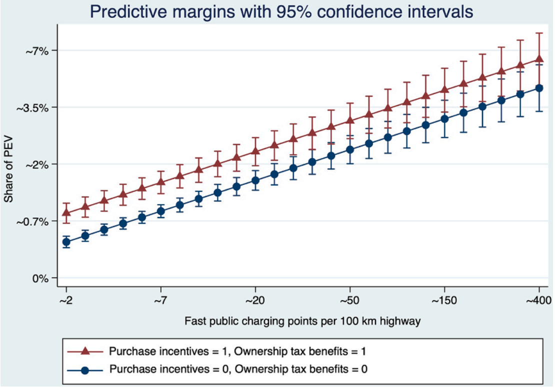

Fig. 3. Predicted PEV market share of new registrations with increases in fast charging points per 100 km highway and with or without a purchase incentives policy.

Kraay standard errors. Using the variance inflation factors (VIF), we can establish whether there is a presence of collinearity in the model. All VIF values are below threshold levels except for the variable to test the curvilinear effect of the first charging variable, which we should expect, suggesting that the explanatory variables are independent of one another. Furthermore, all F-statistics are significant. As the fixed-effects estimator with time control and the Driscoll-Kraay standard errors are robust to both heteroscedasticity and serial correlation, reasonably unbiased model estimations are ensured.

Looking first at the effect of charging infrastructure we can see that normal charging points per capita displays a curvilinear effect on PEV market shares. The effect is marginally negative to about ~ 7 normal chargers per 100.000 before it is positively correlated with increased market shares. Observing this effect graphically, Fig. 2 presents the predicted PEV market share of new registrations with an increase in normal public chargers per capita (100.000) with or without a purchase incentives and ownership tax benefits based on model 2 in Table 3. The logged transformed variables have been converted to their equivalent share in % on the y-axis and the number of normal chargers per capita on the x-axis in the figure. The prediction displays that increases in charging infrastructure can have substantial effects on market shares of PEVs and that the effect is stronger at the right end of the curve, and the difference with or without having purchase incentives and ownership tax benefits is relatively smaller, but certainly not trivial.

Next, fast charging infrastructure is positive and significant at the 1% level across all six models in Table 3. Looking at the effect graphically in Fig. 3, the prediction based on model 2 in Table 3 shows that an expansion of fast charging infrastructure per 100 km high increases PEV market share of new car registrations substantially and that the effect is stronger than normal charging and similar to Fig. 2, the difference with or without having purchase incentives and ownership tax benefits is relatively smaller. The logged transformed variables have been converted to their equivalent share in % on the y-axis and the number of fast charging points per 100 km highway on the x-axis in the figure.

The model thus predicts that if European countries build 150 fast chargers per 100 km of highway, PEV market share will increase by ~ 3%, and ~ 5% in a scenario with 400 fast chargers, holding purchase incentives and ownership tax benefits aside (for reference, Norway had 655 fast charging stations per 100 km of highway in 2019).

In summary, the results related to charging infrastructure are in line with Bakker and Trip (2013), Sierzchula et al. (2014), Gnann et al. (2018), Wei et al. (2021) and Greaker (2021), and strongly suggest that policymakers need to focus on providing the necessary regulation, funding, and political conditions for private companies and relevant public entities to upgrade essential local, regional, and continental charging networks and infrastructure in order to enable a shift toward low-emission mobility.

Regarding the effects of electric mobility incentives, there is a positive effect of purchase incentives, in line with the findings of Hardman et al. (2017) and Münzel et al. (2019), but only at the 10% significance level. The positive effect of ownership tax benefits is significant at the 5% level, while the model shows no significant effect for either registration tax benefits or local incentives.

The results for the electric mobility policy packages are interesting and display a positive effect at varying levels of significance. Policy package 3, covering incentives related to purchasing and ownership costs and any local incentives (Pi + Rtb + Otb + Li), displays the strongest effect of the policy packages and is significant at the 1% level. The same is true for policy package 2, which covers incentives related to purchasing and ownership costs (Pi + Rtb + Otb), which displays a weaker effect than policy package 3 but is also significant at the 1% level. Policy package 4, which covers incentives aimed at private and company purchases (Pi + Ctb), is significant at the 5% level but is the weakest effect of the packages. Finally, policy package 1, which covers all the incentives (Pi + Rtb + Otb + Ctb + Li) tested is significant, but at the 10% level and displays a considerably smaller effect than the strongest effect in policy package 3.

Finally, looking at the control variables in Table 3, we can see that the estimated coefficients for urban population show a positive and significant effect on PEV market share of new registrations at the 1% level across all six models. These results are in line with the findings of Lane and Potter (2007) and Gallagher and Muehlegger (2011) showing that urbanization increases PEV market shares, despite limited charging opportunities in dense urban centers, which could suggest that greater urbanization would also allow PEVs with limited range, higher utilization and convenience.

The effect of mean pump prices for petrol and diesel is also positive and significant at the 10% level across nearly all models except model 5, in line with previous research on the price effects on consumer choices. Interestingly, the converse effect on cheaper electricity prices cannot be shown to have any impact on the PEV market share. One explanation for this non-finding is that the mean price of a liter of petrol and diesel in the sample is around 2.1 US dollars, while in contrast the mean price of a kWh of electricity is 0.17 euro, and while these are not fully comparable prices, charging an electric car is considerably cheaper than using petrol or diesel. Therefore, it is possible to argue that an increase in pump prices might matter, while an increase or decrease in electricity prices makes little difference for consumer choices. As European countries deal with increased electricity demand from electrification, ways to regulate price signals and reduce peak demand will be an interesting development and will likely have a larger impact than the mean price itself.

The effect of GDP per capita is negative and significant at varying levels across five out of the six models, while not significant in model 2. At first glance, this negative GDP effect seems surprising, but the fixed-effects estimation suggests that higher income changes do not matter much for PEV market shares. The negative effect rather suggests that some of the wealthiest units (countries) in Europe are laggards (e.g., Switzerland and Luxembourg). We could, however, expect income level to matter for PEV share. Running the model with random effects (Model 7 Table A2) indeed shows a positive effect, but the result is non-significant. Sierzchula et al. (2014) found no significant relationship between EV market share and electricity prices in their 2012 sample but did not find any positive correlation with urban density, fuel prices, or GDP indicators either.

4.1. Robustness checks

The main models in Table 3 are estimated without outliers in Table A2 (models 8–12) using Cook's distance (Cook, 1977). These models display relatively similar results to the main models in Table 3, implying the robustness of the results. Table A3 shows models estimated with 2020 included. The results are similar except for the non-significant effect of purchase incentives in model 14, while policy packages including purchase incentives still display significant positive effects on PEV shares. Finally, Tables A4 and A5 (with 2020) show the robustness tests with the market share of battery electric vehicles only as the dependent variable. Models 19–24 in Table A4 display similar results to PEV models except that purchases incentives, ownership tax benefits, and policy package 4 are non–significant. Additionally, residential electricity prices negatively correlate with BEV market shares, indicating that higher electricity prices reduce BEV market shares. Table A5, which includes 2020, displays nearly identical results.

In sum, the results are relatively stable across nearly all 30 models in the analysis. The most noteworthy and stable result across all the models is the effect of charging infrastructure on PEV market developments. While the effect of purchase incentives and ownership tax benefits are positive and significant in the main model, the results are not reproduced in robustness tests. However, the models indicate that countries with policy packages for electric mobility have higher market shares of PEVs, suggesting another robust empirical finding.

As battery and PEV prices continue to go down, it is just a matter of time before PEVs will be price competitive without incentives (e.g., DNV GL, 2020; BNEF, 2020; EVO, 2020a,b), which again creates a reason for governments to roll back on lucrative financial incentives. If then, as the results of the analysis seem to suggest, charging infrastructure availability and convenience becomes as, or even more, important for consumers as the upfront financial cost, it might be more cost-effective to provide support for the infrastructure of charging—which can be used by everyone with a PEV—rather than subsidizing the vehicles as they approach cost parity with ICEVs. However, this inflection point has not happened yet. Until then, governments should focus on a mix of policies—supporting charging infrastructure and especially fast charging infrastructure while the model shows that policy packages combining several electric mobility packages are more effective than single policies.

4.2. Limitations

Despite having the latest available data and reasonably sophisticated models covering key electric mobility policies and charging infrastructure variables, this analysis is not without drawbacks. One key question related to the effect of charging infrastructure is the issue of reverse causality. One way to establish the arrow of causality in these situations is to employ an instrumental variable (IV) regression. It is notoriously hard to find a sufficient variable for this purpose. The choice made here is renewable energy's share of total electricity generation, the argument being that countries with high renewable shares in their power generation have pursued charging infrastructure buildout, and that those with lower renewable energy shares might have been slower to adopt strategies and support for charging buildout as their power mix is more emission intensive. I then attempt to prove that charging infrastructure does indeed increase PEV shares, and not the other way around. However, for the model to be valid, establishing the arrow of causality for these particular variables is clearly important. The IV regression shows that the parameters and test results are adequate and in line with those provided by Baum et al. (2007). We can with reasonable certainty establish that increases in charging infrastructure do lead to higher PEV shares. Following this, we should be wary of an unbridled belief in the predictive power of econometric models based on historical data (see for instance the Lucas critique, Lucas, 1976), especially early in a worldwide transition.

The data used in the analysis only distinguish between whether or not a country has a specific electric mobility policy in place in a given year. Ideally it would be best to have access to concrete monetary values on the incentives in each country in a given year, and the lack of more calibrated indicators differentiating between high and low financial incentives has to be kept in mind when interpreting the results. Finally, the analysis lacks an indicator measuring home- or privately-owned charging points. The conclusions should not be swayed to a large extent by this, but it is nevertheless a key indicator to keep an eye on going forward. If anything, it makes the infrastructure story more rather than less credible, as it is reasonable to assume that, especially in big cities with difficult and crowded parking situations, charging infrastructure will remain a problem needing solutions. According to the latest projections by

Table A1
Selected modern plug-in hybrids from auto manufacturers.

Car model	CO_2 emissions in g/km - NEDC (collected from manufacturer)
Audi A3 Sportback e-tron 2018	37
Audi Q7 e-tron 2018	48
Hyundai IONIQ Plug-in Hybrid 2018	26
Volkswagen Golf GTE 2020	38
Mercedes-Benz C 350 2018	49
Mercedes-Benz E 350e 2018	49
Mitsubishi Outlander Plug-in Hybrid 2018	46
Volvo V60 Plug-in Hybrid 2018	48
Volvo XC60 T8 Twin Engine 2018	49
Volvo XC90 T8 Twin Engine 2018	49

Table A2
Robustness testing for the effect of charging infrastructure and electric mobility policies on the share of PEV registrations in Europe.

	(7)	(8)	(9)	(10)	(11)	(12)
Variables	Share of PEV - Random effects	Share of PEV using Cook's distance	Share of PEV using Cook's distance	Share of PEV using Cook's distance	Share of PEV using Cook's distance	Share of PEV using Cook's distance
Normal chargers per capita (*logged*)	−0.234***	−0.173*	−0.123*	−0.169*	−0.208***	−0.190**
	(0.0465)	(0.101)	(0.0696)	(0.0795)	(0.0645)	(0.0823)
Normal chargers per capita (*squared)*	0.0804***	0.0574*	0.0523**	0.0542*	0.0662**	0.0544*
	(0.0144)	(0.0276)	(0.0225)	(0.0248)	(0.0239)	(0.0250)
Fast public charging points (*logged*)	0.250***	0.315***	0.260***	0.293***	0.251***	0.289***
	(0.0311)	(0.0301)	(0.0207)	(0.0171)	(0.0215)	(0.0211)
Purchase incentives (*pi*)	0.108	0.263**				
	(0.0745)	(0.0889)				
Registration tax benefits (*Rtb*)	0.0363	0.0647				
	(0.0423)	(0.0802)				
Ownership tax benefits (*otb*)	0.166***	0.0849**				
	(0.0413)	(0.0296)				
Local incentives (*li*)	−0.0293	−0.181				
	(0.116)	(0.101)				
Policy package 1			0.210**			
			(0.0876)			
Policy package 2				0.461***		
				(0.0499)		
Policy package 3					0.453***	
					(0.0834)	
Policy package 4						0.185*
						(0.0984)
Urban population	0.00906*	0.000346	0.00424	0.0305	−0.0198	−0.0126
	(0.00446)	(0.0411)	(0.0441)	(0.0473)	(0.0330)	(0.0578)
GDP per capita (*logged*)	0.0848	−0.416	−0.943**	−0.846**	−1.008***	−0.962**
	(0.101)	(0.312)	(0.334)	(0.342)	(0.270)	(0.351)
Residential electricity price	−0.821*	−2.781	−1.237	−3.455	−1.751	−2.489
	(0.384)	(1.984)	(2.205)	(2.385)	(2.198)	(2.081)
Mean pump price petrol & diesel	0.0324	0.347*	0.246*	0.312**	0.217*	0.256*
	(0.0331)	(0.179)	(0.126)	(0.125)	(0.103)	(0.122)
Constant	−1.481	3.974	8.932	6.165	11.50**	10.72
	(1.282)	(6.321)	(6.446)	(6.714)	(4.751)	(7.924)
Observations	352	242	257	244	256	250
Number of countries	32	28	31	30	31	31
Time FE	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0$.

Table A3
Robustness testing for the effect of charging infrastructure and electric mobility policies on the share of PEV registrations in Europe including 2020.

	(13)	(14)	(15)	(16)	(17)	(18)
Variables	Share of PEV	Share of PEV	Share of PEV	Share of PEV	Share of PEV	Share of PEV
Normal chargers per capita (*logged*)	−0.199***	−0.207***	−0.200***	−0.195***	−0.211***	−0.201***
	(0.0453)	(0.0518)	(0.0469)	(0.0430)	(0.0468)	(0.0467)
Normal chargers per capita (*squared)*	0.0727***	0.0709***	0.0724***	0.0703***	0.0741***	0.0703***
	(0.0158)	(0.0185)	(0.0164)	(0.0160)	(0.0162)	(0.0169)
Fast public charging points (*logged*)	0.249***	0.258***	0.251***	0.253***	0.247***	0.253***
	(0.0227)	(0.0238)	(0.0218)	(0.0230)	(0.0217)	(0.0232)
Purchase incentives (*pi*)		0.106				
		(0.0726)				
Registration tax benefits (*Rtb*)		−0.0411				
		(0.0434)				
Ownership tax benefits (*otb*)		0.131**				
		(0.0576)				
Local incentives (*li*)		0.0191				
		(0.117)				
Policy package 1			0.173*			
			(0.0945)			
Policy package 2				0.187***		
				(0.0581)		
Policy package 3					0.318***	
					(0.0910)	
Policy package 4						0.106*
						(0.0496)
Urban population	0.0596***	0.0606***	0.0499***	0.0624***	0.0429***	0.0557***
	(0.00669)	(0.0119)	(0.00675)	(0.00808)	(0.00724)	(0.00726)
GDP per capita (*logged*)	−0.155	−0.160	−0.263	−0.267	−0.341	−0.185
	(0.250)	(0.222)	(0.250)	(0.290)	(0.266)	(0.263)
Residential electricity price	0.209	−0.297	0.0287	−0.320	−0.320	−0.0696
	(1.107)	(1.092)	(1.117)	(1.270)	(1.145)	(1.132)
Mean pump price petrol & diesel	0.275***	0.297***	0.263***	0.277***	0.249***	0.271***
	(0.0350)	(0.0562)	(0.0353)	(0.0387)	(0.0365)	(0.0351)
Constant	−3.313	−3.305	−1.449	−2.293	−0.0670	−2.671
	(2.900)	(2.718)	(2.742)	(3.280)	(2.970)	(3.056)
Observations	384	384	384	384	384	384
Number of countries	32	32	32	32	32	32
Time FE	YES	YES	YES	YES	YES	YES

Bloomberg New Energy Finance – EVO 2019, about 290 million charging points will be needed globally by 2040, and while home chargers will be by far the largest category, it is estimated that around 12 million public charging points will be needed as home options are either saturated or unavailable (e.g. in dense cities) (EVO, 2020a). The importance of charging networks is arguably even more critical at the start of the low-emission mobility transition, in order to dispel range anxiety and increase the convenience for PEV owners and those deciding whether or not to become PEV owners. This type of data will inevitably become available at some point in the future as the low-emission mobility transition goes forward, but does not exist today. This should be kept in mind while interpreting the results. Another variable that would be interesting to include is the price of the vehicles. PEVs are still more expensive than ICEVs in most markets and although the gap is rapidly narrowing—together with lower costs of total ownership—they are still not price competitive. For future research, comparative price data for PEV to ICEV counterparts would be interesting.

5. Conclusions and policy implications

The results of the empirical analysis show that increasing charging infrastructure, and fast charging infrastructure in particular, leads to higher PEV market shares. Purchase incentives and ownership tax benefits are positive and significant, but the effect is notably less robust across models. The electric mobility policy packages tested are significant across most model specifications and the policy package that includes incentives related to purchasing and ownership costs and local incentives exhibits the most robust finding of the policy packages tested in the analysis. Furthermore, the empirical evidence from this European analysis suggests that increased urbanization and higher fuel prices for petrol and diesel correlate with higher shares of PEV of new car sales. The results and the following discussion provide some support for the view of the energy transition as a process of structural rather than incremental change, where infrastructure can be seen as more enabling and more important than personal incentives. There is strong evidence for the importance of public charging points and an even stronger effect of fast public chargers for PEV adoption. Some of the personal incentives also have a positive and significant effect across model specifications but as the preceding discussion has shown, although incentives are an important tool for policymakers, they are not necessarily sufficient to lead to structural change. These conclusions suggest that to enable wider PEV adoption policymakers should focus as much attention on charging infrastructure, especially fast charging infrastructure, as they so far have on personal incentives. The implications of these conclusions are in line with the notion that though personal incentives and price signals are certainly important, they will only get us so far. In order to massively reduce emissions

Table A4
Effect of charging infrastructure and electric mobility policies on the share of BEV registrations in Europe.

	(19)	(20)	(21)	(22)	(23)	(24)
VARIABLES	Share of BEV	Share of BEV	Share of BEV	Share of BEV	Share of BEV	Share of BEV
Normal chargers per capita (*logged*)	−0.230***	−0.240***	−0.231***	−0.230***	−0.240***	−0.232***
	(0.0544)	(0.0653)	(0.0576)	(0.0565)	(0.0627)	(0.0557)
Normal chargers per capita (*squared)*	0.0695***	0.0704***	0.0686***	0.0682***	0.0707***	0.0684***
	(0.0180)	(0.0204)	(0.0183)	(0.0184)	(0.0194)	(0.0182)
Fast public charging points (*logged*)	0.184***	0.189***	0.186***	0.188***	0.182***	0.186***
	(0.0163)	(0.0162)	(0.0156)	(0.0147)	(0.0167)	(0.0153)
Purchase incentives (*pi*)		0.0526				
		(0.0547)				
Registration tax benefits (*Rtb*)		0.0343				
		(0.0223)				
Ownership tax benefits (*otb*)		0.0361				
		(0.0297)				
Local incentives (*li*)		−0.0214				
		(0.0821)				
Policy package 1			0.193**			
			(0.0807)			
Policy package 2				0.182***		
				(0.0320)		
Policy package 3					0.249**	
					(0.0853)	
Policy package 4						0.0511
						(0.0345)
Urban population	0.0379**	0.0416**	0.0289**	0.0428**	0.0262**	0.0372**
	(0.0146)	(0.0182)	(0.0117)	(0.0184)	(0.0115)	(0.0147)
GDP per capita (*logged*)	−0.0674	−0.0231	−0.213	−0.198	−0.245	−0.0847
	(0.263)	(0.259)	(0.222)	(0.253)	(0.233)	(0.266)
Residential electricity price	−1.704**	−1.870***	−1.892***	−2.340***	−2.133***	−1.849***
	(0.556)	(0.522)	(0.581)	(0.541)	(0.585)	(0.566)
Mean pump price petrol & diesel	0.106	0.119	0.0867	0.106	0.0749	0.103
	(0.115)	(0.124)	(0.111)	(0.121)	(0.113)	(0.116)
Constant	−2.014	−2.743	0.188	−0.951	0.761	−1.760
	(3.819)	(3.990)	(3.121)	(3.935)	(3.182)	(3.860)
Observations	352	352	352	352	352	352
Number of countries	32	32	32	32	32	32
Time FE	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses.
*$p < 0.1$.
*** $p < 0.01$.
** $p < 0.05$.

in the transportation sector, governments around Europe—and the world for that matter—need to create the frameworks and regulatory conditions, and likely in some cases and areas a sufficient support system, for relevant actors to upgrade charging infrastructure with sufficient charging speeds to make it convenient for consumers to own a PEV.

These conclusions are also timely, as governments around the world are attempting to reboot their economies after lockdowns and global economic slowdown following their efforts to slow down the spread of COVID-19. As wise as attempting to green the economy while rebooting it might seem, policymakers need to take note of the empirical effects of increasing charging infrastructure on PEV adoption in the European sample. Renewable energy was the recipient of major stimulus packages around the world after the 2008 financial crisis, and electric mobility and infrastructure could play a similar role in the aftermath of the pandemic and indeed seem to be part of many post-2020 stimulus packages. Infrastructure requires more governmental involvement, coordination, and regulatory consistency than implementing personal incentive schemes, but is clearly no less important. Given how far the world still has to go in transforming the transportation sector, massive reductions in emissions and the increased efficiency of the transportation system are at stake.

Data Availability

The dataset related to this article can be found at Anonymized link, an open-source online data repository hosted at Mendeley Data (Sæther, 2022).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table A5
Robustness testing for the effect of charging infrastructure and electric mobility policies on the share of BEV registrations in Europe including 2020.

	(25)	(26)	(27)	(28)	(29)	(30)
VARIABLES	Share of BEV	Share of BEV	Share of BEV	Share of BEV	Share of BEV	Share of BEV
Normal chargers per capita (*logged*)	-0.271^{***}	-0.283^{***}	-0.272^{***}	-0.267^{***}	-0.280^{***}	-0.271^{***}
	(0.0537)	(0.0622)	(0.0554)	(0.0525)	(0.0585)	(0.0539)
Normal chargers per capita (*squared)*	0.0844^{***}	0.0856^{***}	0.0840^{***}	0.0820^{***}	0.0854^{***}	0.0833^{***}
	(0.0171)	(0.0191)	(0.0175)	(0.0168)	(0.0178)	(0.0173)
Fast public charging points (*logged*)	0.181^{***}	0.184^{***}	0.183^{***}	0.185^{***}	0.179^{***}	0.182^{***}
	(0.0193)	(0.0190)	(0.0190)	(0.0188)	(0.0196)	(0.0191)
Purchase incentives (*pi*)		0.0434				
		(0.0481)				
Registration tax benefits (*Rtb*)		0.0266				
		(0.0276)				
Ownership tax benefits (*otb*)		0.0436				
		(0.0314)				
Local incentives (*li*)		0.0179				
		(0.0868)				
Policy package 1			0.165^{**}			
			(0.0705)			
Policy package 2				0.174^{***}		
				(0.0223)		
Policy package 3					0.240^{***}	
					(0.0732)	
Policy package 4						0.0464
						(0.0313)
Urban population	0.0437^{**}	0.0447^{**}	0.0344^{**}	0.0463^{**}	0.0311^{**}	0.0420^{**}
	(0.0149)	(0.0157)	(0.0117)	(0.0163)	(0.0116)	(0.0153)
GDP per capita (*logged*)	0.283	0.280	0.179	0.178	0.142	0.270
	(0.293)	(0.280)	(0.294)	(0.306)	(0.299)	(0.298)
Residential electricity price	−1.134	-1.368^{*}	-1.307^{*}	-1.628^{*}	-1.534^{*}	−1.256
	(0.717)	(0.680)	(0.705)	(0.777)	(0.706)	(0.752)
Mean pump price petrol & diesel	0.186^{***}	0.189^{***}	0.174^{***}	0.187^{***}	0.166^{***}	0.184^{***}
	(0.0292)	(0.0334)	(0.0300)	(0.0312)	(0.0306)	(0.0295)
Constant	−6.256	−6.274	−4.470	−5.303	−3.802	−5.976
	(4.051)	(3.941)	(3.835)	(4.241)	(3.877)	(4.119)
Observations	384	384	384	384	384	384
Number of countries	32	32	32	32	32	32
Time FE	YES	YES	YES	YES	YES	YES

Driscoll-Kraay standard errors robust to temporal and spatial autocorrelation in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Appendix A

see Tables A1–A5.

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