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Effectiveness and Heterogeneous Effects of Purchase Grants for Electric Vehicles

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Abstract

We evaluate German purchase subsidies for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) using data on new vehicle registrations in Germany during 2015-2022. We account for confounding time trends and interacting EU-level CO_2 standards using neighboring countries as a control group. We find that 40% of BEV and 25% of PHEV registrations were subsidy-induced. The program had strong distributional effects, with greater uptake in wealthier and greener counties. We estimate implied abatement costs of 870 euro per ton of CO_2 for BEVs and 2,470 euro for PHEVs, suggesting that policy makers should re-balance support schemes away from PHEVs.

Keywords Decarbonizing road transport · Electric mobility · Purchase subsidies · Policy effectiveness · Distributional effects of climate policy

JEL Classification $~Q54 \cdot Q58 \cdot H23 \cdot R48$

1 Introduction

Decarbonizing transportation is an increasingly urgent goal for national and international climate policy, as the transport sector represents about one quarter of global greenhouse gas (GHG) emissions and lags behind other sectors with respect to abatement. Given that poli-

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cymakers worldwide are increasingly accepting the target of climate neutrality by mid-century, the transport sector must be largely decarbonized by 2050. Passenger cars represent the greatest share of GHG emissions from transportation by far. Therefore, policies targeting emissions from cars are important planks in countries' climate policy packages. Consumer subsidies for the purchase of new electric vehicles have emerged as a central element in many countries' climate policy mix targeting the transport sector, and are being used around the world in major economies, including the U.S., China, Japan and Germany (IEA 2022).¹ For example, the U.S. significantly expanded purchase incentives for electric vehicles in its 2022 Inflation Reduction Act (Congress 2022). However, subsidies may be not effective and non-additional, e.g. if consumers would have bought the respective vehicles without the subsidy (e.g. Mian and Sufi 2012; Hoekstra et al. 2017) or if interacting policies– in our setting, especially EU-level CO_2 emission standards– also play an important role in driving the uptake.

Moreover, purchase subsidies are only relevant for customers willing and able to purchase a new car. Thus, the subsidy program may disproportionately benefit wealthier buyers with a greater concern for the environment (e.g. Allcott et al. 2015; Borenstein and Davis 2024), which raises distributional concerns and may negatively affect the acceptance of purchase subsidies by the general population. Therefore, in addition to analyzing the effectiveness of purchase subsidies understanding the distributional implications of this policy is crucial.

This paper studies the effectiveness and heterogeneous effects of the purchase subsidy program for electric vehicles (EVs) in Germany, one of the most important car markets worldwide and the home market of some of the largest car manufacturers. The German federal government introduced substantial consumer grants for the purchase of battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), with total subsidy amounts of up to 9,000 euro per purchased vehicle.

Our main contributions are twofold: First, we estimate the causal effect of a subsidy program on the uptake of BEVs and PHEVs using highly granular information on the universe of vehicle registrations in Germany. For the identification, we exploit time specific policy variation and account for confounding time trends and other relevant EU-wide policy using neighboring European countries as a control group. Second, we provide a detailed analysis of heterogeneous policy effects with respect to income, ideology– as proxied by the share of Green Party votes in federal elections– and degree of urbanization– proxied by population density. In this way we contribute not only to understanding whether purchase subsidies have distributional impacts but also to disentangling the main drivers of distributional effects.

For the empirical analysis, we combine highly granular data on monthly registrations of new vehicles at the vehicle model level from the German Federal Motor Transport Authority (*Kraftfahrt-Bundesamt*) with vehicle list prices from ADAC, the German motorists' association, to determine which vehicles are eligible for the subsidy and to perform a baseline analysis of the policy's average effectiveness on the registration of eligible vehicle models, normalized by county population.

We disentangle the effects of the largely concurrent increases in the ambition level of the German subsidy scheme and the European fleet level CO_2 standards. We do so by following two approaches which both exploit BEV and PHEV registration data at the national level

¹Cf. Rapson and Muehlegger (2023) for an overview of the economics of electric mobility.

from other European countries provided by the European Alternative Fuels Observatory (EAFO) of the European Commission. We focus on neighboring countries that did not experience major concurrent changes in the stringency of their policy frameworks to account for the impact of the simultaneous European policy. In a first approach, we apply the synthetic control method at the aggregate country level. The algorithm weights the donor pool countries to fit in the evolution of registrations between Germany and the synthetic control group before the treatment period. This analysis provides us with baseline results, but does not allow us to exploit variation across German counties and is therefore not suited to analyzing the heterogeneous effects of the subsidy policy. For this reason, we also implement a second approach. Similar to the idea of the first approach, we de-trend the registrations data over time in the German counties by using BEV and PHEV registration data from the same set of donor pool countries as in the synthetic control application. We then use the de-trended data in an event study approach to estimate the causal effects and effect heterogeneity of the German subsidy scheme. Sensitivity checks show that our results are robust to changing the composition of the group of control countries in both approaches.

Our results show that the purchase grant program was effective at increasing the sales of both subsidized BEVs and PHEVs. The data suggest that county-level BEV registrations rose by around 1,400% over time, and by about 600% for PHEVs. However, based on our identification strategy, we find that only a fraction of new BEV and PHEV registrations can be attributed to the German subsidy scheme. In particular, our results suggest that only 40% of BEV and 25% of PHEV registrations are subsidy-induced, implying that the rest of the increase in registrations is driven by general time trends and EU regulations on fleetlevel CO_2 intensity. We further find that the effects are highly heterogeneous with respect to income and "greenness", although somewhat different patterns emerge for BEVs and PHEVs. For BEVs, heterogeneity is very pronounced. The purchase subsidy for BEVs was disproportionately taken up by individuals in wealthier counties and with a higher share of Green Party votes. For PHEVs, heterogeneous effects are also present but muted compared to BEVs. In contrast, differences in the degree of urbanization, as proxied by population density, does not play a strong role in the adoption of either BEVs or PHEVs, suggesting that concern regarding vehicle range is not a major driver of BEV/PHEV uptake. Based on the empirical results, we provide an estimate of the environmental effectiveness of the subsidy program. The abatement costs are substantial. Our baseline estimates imply abatement costs of about 870 euro per tonne of CO2 for BEVs and almost 2,470 euro per tonne of CO_2 for PHEVs.

Using our empirical findings, we draw four main policy conclusions. First, despite the sizable impact of the reform on EV uptake, our results highlight the substantial financial commitment involved and the program's limited additional effectiveness. Second, the analysis of effect heterogeneity shows that the subsidy scheme involves a substantial transfer to individuals in high-income regions, leading to distributional concerns over policy acceptance among the general population. Third, we show that the implied CO_2 abatement costs of the program are much higher for PHEVs compared to BEVs. The stark contrast in the relative performance of PHEV and BEV subsidies suggests that policymakers worldwide should strongly consider differentiating between the two technologies when designing climate policy in the transport sector. Fourth, the abatement costs for BEVs may be justified given the goal of unleashing learning-by-doing and economies of scale effects and the ambitious time frame of largely decarbonizing the transportation sector by mid-century. In

addition, the ongoing decarbonization of the German power grid, as in other countries with increasing shares of electricity from renewable energy, will further mechanically decrease abatement costs in the future.

A growing literature studies the effectiveness of subsidy schemes and concludes that subsidies are an important determinant of EV uptake (e.g. Jenn et al. 2018; Clinton and Steinberg 2019; Münzel et al. 2019; Azarafshar and Vermeulen 2020). Our paper is related to the stream of the literature using quasi-experimental variation based on granular data on vehicle uptake to identify causal effects. An important existing contribution is Muehlegger and Rapson (2022), who analyze the effectiveness of a BEV purchase program in California targeting low- and middle-income buyers. Chen et al. (2021) and Li et al. (2022) add evidence on the impacts of purchase subsidies in China, while Wang et al. (2022) analyze the impact of a demonstration program promoting electric vehicles in a number of Chinese cities. In a European context, Cerruti et al. (2024) evaluate, among other policies, the effectiveness of purchase subsidies for electric vehicles in Switzerland by exploiting variation at the cantonal level. We extend this literature by analyzing the effectiveness of purchasing subsidies in Europe's most important car market. Moreover, we contribute by carefully investigating the heterogeneity of policy effectiveness, which allows us to pin down some of the main drivers of the baseline effect. Our analysis of heterogeneous effects is motivated by and speaks to emerging evidence suggesting that demand for electric vehicles increases strongly with income (Bigler and Radulescu 2022), that high-income households disproportionately capture government support for electric vehicles (Borenstein and Davis 2024), and that electric vehicle uptake may in part be driven by an effort to signal green attitudes (Sexton and Sexton 2014).

We also contribute to the subset of the literature focusing on the environmental effectiveness of purchase incentives. Holland et al. (2016) provide an estimate of the environmental benefits and costs due to air pollution and GHG emissions of EV purchase support schemes in the US. They conclude that the net benefits are modest in terms of GHG emissions and highly heterogeneous across space, with low-income areas receiving net environmental costs due to air pollution (Holland et al. 2019). Thus, whether EV support programs are welfare-enhancing strongly depends on local conditions across the US. In a related study, Xing et al. (2021) consider substitution patterns using U.S. survey data on new vehicle purchases and conclude that the environmental effectiveness of current support schemes for EVs is limited, as EVs typically substitute for relatively low-polluting vehicles. Rapson and Muehlegger (2023) and Linn (2022) stress the low cost-effectiveness of uniform purchase subsidies, due to the inability to exclude infra-marginal consumers. Yet Roberson and Helveston (2022) show that purchase rebates may be more effective with respect to generating demand for EVs than tax incentives, a point echoed by Cerruti et al. (2024). Yang and Tang (2019) show that while Chinese purchase subsidies for EVs lead to increases in EVs registrations, the environmental performance of purchase subsidies is negative, as they increase CO_2 emissions from electricity generation due to incentivizing purchases of many additional vehicles. Our own calculations focus on the environmental effectiveness of the German subsidy with respect to GHG emissions. Thus, we not only provide estimates of abatement costs for a European subsidy scheme, but we also document the stark difference in environmental effectiveness between BEV and PHEv subsidies. In addition, some of our abatement cost scenarios account for different substitution patterns in line with Xing et al. (2021).

Finally, our paper is also related to a complementary literature studying the role of policy choices on decisions by players in the car market using a more structural approach. A range of papers address the indirect network effect on the two sides of the BEV market, charging infrastructure and BEV adoption (Li et al. 2017; Springel 2021; Li 2019). This leads to a "chicken-and-egg" problem, where vehicle adoption depends on the availability of sufficient charging infrastructure, while investment in charging infrastructure becomes more attractive with an (expected) larger BEV fleet. By exploiting variation induced through subsidy implementations or grocery store density, these authors derive similar conclusions. They find that, despite both subsidies for vehicle purchases and charging infrastructure being effective, the latter are consistently more relevant. In a somewhat distinct contribution, Remmy (2022) also estimates a structural model of the vehicle market, using an aggregate version of the data from Germany used in this paper, and investigates the effects of subsidies on decisions of car manufacturers with respect to price and range of vehicles.

2 Background

2.1 Subsidy Policy

Germany's federal government implemented a package of support measures with the goal of establishing Germany as a lead market for electric mobility. A major component is the introduction of consumer grants for the purchase of battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

The consumer purchase grant program was initiated in 2016, with vehicles newly registered after May 18, 2016, being eligible for subsidies (BMWi 2016). Subsidies are shared by the federal government and by vehicle manufacturers. The government paid out 2,000 euro for the purchase of an BEV and 1,500 euro for a PHEV, conditional on the purchase receipt documenting a manufacturer rebate of an equal amount. Vehicles with a list price of up to 60,000 euro were eligible for the grant program.² As the mandated manufacturer rebate is likely to interact with other purchase incentives offered by manufacturers, we consider the government amount as the baseline treatment intensity.³ The initial grant program had a total budget of some 600 million euro (BMF 2021).

The purchase program became progressively more ambitious. In February 2020, both the government grant and manufacturer rebates increased by 50% for vehicles with a listed price of up to 40,000 euro, reaching a total value of 6,000 for BEVs and 4,500 euro for PHEVs. Cars newly registered after November 5, 2019, were eligible for the increased grants (BMWi 2020a). For vehicles with a listed price between 40,000 and 65,000 euro, government grants and required manufacturer rebates increased by 25% each, to a total value of 5,000 euro for BEVs and 3,750 euro for PHEVs. Moreover, the federal government extended the duration of the purchase program (at the original grant level prior to 2019) through the end of 2025, with a total budget commitment of 2.09 billion euro for the 2020-2023 period (BMF 2021). Shortly after, in June 2020 the government increased the subsidy

² For the purpose of this paper, list price refers to the base list price of a model, i.e. the list price of the version of the model without optional equipment and add-ons.

³As transaction prices are not available to us, the extent to which the manufacturer rebate substituted for other rebates normally provided during the purchase negotiation cannot be analyzed.

Table 1 Overview of subsidy		No	Reform 1	Reform 2	
over time		policy	Introduction	1^{st} Increase	2 nd In- crease
		Jan 2015	May 2016	Nov 2019	June 2020
	BEV				
	< €40.000				
	Govern. share	NA	2,000	3,000	6,000
	Total subsidy	NA	4,000	6,000	9,000
	€40.000- €65.000				
	Govern. share	NA	2,000*	2,500	5,000
	Total subsidy	NA	4,000*	5,000	7,500
	PHEV				
	< €40.000				
	Govern. share	NA	1,500	2,250	4,500
The table shows the tiers	Total subsidy	NA	3,000	4,500	6,750
of the German subsidy scheme for BEVs and PHEVs including the subsidy levels and their evolution over time. The maximum list price for eligibility during Reform 1 was 60,000 euro.	€40.000- €65.000				
	Govern. share	NA	1,500*	1,875	3,750
	Total subsidy	NA	3,000*	3,750	5,625

even further. The amount of the government share of purchase grants was doubled compared to the level set in November 2019, while the manufacturer share remained unchanged (BMWi 2020c), bringing the total grant amount up to 9,000 euro per BEV for vehicles with listed prices below 40,000 euro and 7,500 euro for those with listed prices between 40,000 and 65,000. A further 2 billion euro was also added to the total budget of the program (BMF 2021). In late 2020, the doubling of the government share was extended through 2025 (BMWi 2020b).⁴

In Table 1 we summarize the key facts of the different policy changes. Given the short interval between the two subsidy increases, we cannot separately identify the effects of Policy 2 and Policy 3 in the empirical analysis. Instead, we estimate the joint effect of the two policies, which we define as Reform 2.5^{5}

⁴According to estimates in the grey literature, the current level of the subsidy is making BEVs in the lower (below 40,000 euro) and middle (40,000 - 65,000 euro) market segments competitive with comparable internal combustion models, while highly priced BEVs were already competitive without receiving subsidies (Agora Verkehrswende 2021).

⁵On the contrary, we argue that the causal effect of Reform 2 can be disentangled from long-term effects of Reform 1. Given a time window of more than three years between these reforms, it is unlikely that any long-term effects of Reform 1 coincide with the introduction of Reform 2.

Table 2 Pairwise correlations of heterogeneity dimensions		HH Income	Population density	Green party vote share
	HH Income	1.00	-0.08	0.43
	Population density	-0.08	1.00	0.41
	Green party vote share	0.43	0.41	1.00

In addition to purchase grants, the government also supports electric mobility in additional ways. One major point of intervention is support for the installation of charging infrastructure, a requirement for the viability of BEVs and PHEVs. Stations for rapid charging are of particular interest, as, due to the high charging speed, these represent the closest substitute for traditional gas stations. The government is also deploying its own purchasing power, by setting the target that 20% of its own vehicle fleet shall consist of BEVs. As government agencies are not eligible for subsidies, government purchases generate additional demand for BEVs without crowding out demand for subsidies from other market players, while depressing demand for vehicles with internal combustion engines. Moreover, owners of BEVs receive further privileges, such as freedom from the federal vehicle tax for 10 years for each vehicle, tax incentives for charging vehicles at their owners' work location and privileged parking spaces (see Table 7).

2.2 Potential for Heterogeneous Effects

Our setting of a rather untargeted policy scheme offers a lot of potential for heterogeneity in the uptake of subsidy payments. Analyzing such heterogeneity can shed light on some key mechanisms behind the uptake of electric vehicles. In this paper, we explore effect heterogeneity along three dimensions, starting with income– a canonical dimension along which to delineate effect heterogeneity (Muehlegger and Rapson 2022). Second, the literature shows that energy efficiency subsidies are especially taken up by individuals with an environmentalist orientation (Allcott et al. 2015). We test for these patterns by considering attitudes toward environmental issues, proxied by the share of the Green Party voting in the 2017 federal election, which is the federal election closest to the introduction of the subsidy policy. Third, we consider the extent to which subsidy take-up depends on the degree of urbanization, which we view as an indication of the extent to which range anxiety (Li et al. 2017) may be a factor in EV take-up in our setting.

To explore heterogeneity, we map each German county into the quartile of the distribution it belongs to with respect to income, green vote share, and population density. It is important to note that the categorization of the regions according to the different dimensions is correlated. In Table 2, we present pairwise correlations of our three dimensions of heterogeneity. Income and Green Party share are positively correlated, with a correlation coefficient of 0.43, while income and population density are almost uncorrelated. Moreover, population density and Green Party vote share are also positively correlated, with a correlation coefficient of 0.41.

Figure 1 shows the geographical distribution of the counties according to the these three variables. A comparison of the income and Green Party vote share variables is especially instructive: one factor common to these variables is the geographic location of counties



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between East and West Germany. Most counties in Eastern Germany belong to the bottom quartiles according to both average household income (Fig. 1a) and share of the Green Party vote (Fig. 1b), with the exception of some (sub-)urban areas. Many Eastern German counties are also in the bottom quartile according to population density, although the picture here is less clear-cut than with income distribution and Green Party vote share. Therefore, the former division in Germany is an important source of variation in all three of the variables used for heterogeneity analysis.

3 Data

3.1 Data Sources

The main data source used in this paper is a dataset from the German Federal Motor Transport Authority (*Kraftfahrt-Bundesamt*). It contains the monthly number of the universe of newly registered vehicles at the vehicle model level aggregated for 399 German counties.⁶ The data includes information about the engine type, i.e. about different classes of internal-combustion engines like gasoline or diesel, plug-in hybrid engines, or battery electric vehicles. Additionally, registrations are distinguished by ownership type, i.e. whether a vehicle is commercially or privately owned.

For our analysis, we use the monthly information for the January 2015 to February 2022 period. Thus, we observe the number of registrations before and after the different policy reforms.

We map registrations of vehicle models into the subsidy policy framework using data on list prices for each model from ADAC (*Allgemeiner Deutscher Automobil-Club*), the German motoring association. Specifically, each BEV or PHEV model is matched to one of three different price segments: vehicles with a list price below 40,000 euro, vehicles with a list price between 40,000 euro and 65,000 euro, and vehicles with a list price exceeding 65,000 euro. Thus, we can identify which vehicles were eligible for the different subsidy levels.⁷ In addition, we match county level information to our dataset. This includes population density information from the German Statistical Office (destatis) and county socioeconomic characteristics from the Federal Institute for Research on Building, Urban Affairs, and Spatial Development. This allows us to classify counties by income, population density, and political preferences, all of which are key dimensions for the heterogeneity analysis.

The original datasets includes more than 20 million registrations over our sample period, of which 1.8% are dropped during the data cleaning process.⁸ In order to reduce the dimensionality of our dataset, we aggregate all relevant information to the county by month level. Thus, we end up with a balanced panel of 399 counties over 86 months. We normalize the

⁶The data consists of cars newly purchased in Germany and cars brought into Germany from abroad. However, the vast majority are newly purchased vehicles.

⁷We do not observe if the owners of the vehicle actually applied for the subsidy. Given the generous financial incentive of the policy and its public salience, we consider any vehicle registration eligible for the subsidy as treated.

⁸We only keep registrations with no missing information on any key variable. Furthermore, we drop registrations from eight PHEV and BEV models that at some point changed price segment between the 40,000-65,000 euro and above 65,000 euro price segments. These vehicle models represent very low market shares amongst their respective engine market segment.

information about registrations to 100,000 inhabitants to account for variation in the size of the different counties.

Finally, in some parts of our analysis we also use total monthly registration data for new BEVs and PHEVs from the European Alternative Fuels Observatory (EAFO) at the European Commission. We focus on seven neighbors of Germany: Austria, Belgium, Denmark, France, Luxembourg, Sweden, and Switzerland.

3.2 Descriptive Overview

Before turning to the econometric analysis, we first provide a descriptive overview of our data. Figure 2 shows overall registrations in Germany by engine type over time. The vertical lines mark the introduction of the reforms. In addition, we highlight in grey the lockdown periods due to Covid-19, which had a large effect on production across the entire economy.

In the pre-reform period, until mid-2017, almost all vehicles in Germany were based on internal combustion engine (ICE) technology: The lines indicating total registrations and total ICE registrations overlap almost perfectly. After the first reform, in May 2016, we see a small increase in the registration of hybrid vehicles and, to a lesser extent, of EVs. While registration of hybrids becomes dynamic before the introduction of the new policies in 2019 and 2020, the demand for EVs stays at very low levels. Only after these reforms we see a clear increase in registrations for both PHEVs and BEVs. By the end of our sample period, in late 2021 and early 2022, PHEVs and BEVs have reached similar registration numbers



Fig. 2 Total number of registrations, by engine type. Note: The figure is based on monthly vehicle registration data from January 2015 through February 2022. The first dotted line indicates the introduction of the subsidy system in May 2016. The second and third dotted lines show the eligibility cutoff of the amendments to the subsidy scheme in November 2019 and June 2020. Grey shaded areas indicate periods of lockdown due to Covid-19.

Sources: German Federal Motor Transport Authority, own calculations

as vehicles with diesel engines, which were on a downward trend for much of our sample period. Finally, we also observe synchronized drops in registrations that affect all engine types during the two lockdown periods due to Covid-19.

In order to gain a better understanding of the evolution of total BEV and PHEV registrations, Fig. 3 describes this evolution by price segment. As seen in Fig. 3a, the total increase in BEV registrations is mostly driven by vehicles with a list price below 40,000 euro. Registrations in this price segment steadily increase after the implementation of the subsidy scheme in May 2016, but they rise dramatically in 2020 and reach the level of more than 20,000 monthly registrations. In contrast, registrations of vehicles with list price above 40,000 euro increase more slowly, never reaching the threshold of 5,000 monthly registrations. When shifting focus to PHEV, Fig. 3b presents a similar but slightly different picture. At the beginning of the sample period, total PHEV registrations for all three price segments are comparable to BEV registrations. However, in this case the total increase over time is driven by both the price segment of vehicles below 40,000 euro and of vehicles between 40,000 and 65,000 euro.

Finally, we present evidence of the heterogeneous developments across counties in Fig. 4. Figure 4a shows the market share of BEVs in all price segments in the year 2021 (the last complete calendar year in our sample period) for all 399 German counties of Germany, while Fig. 4b shows the equivalent information for PHEVs. While market shares for both BEVs and PHEVs often exceeded 20%, it is noteworthy that considerable between-county variation exists. In particular, counties in the former East Germany exhibit substantially lower market shares compared to most Western counties.



Fig. 3 Number of registrations, by engine type and price segment. Note: The figures are based on monthly vehicle registration data from January 2015 through February 2022. The first dotted line indicates the introduction of the subsidy system in May 2016. The second and third dotted lines show the eligibility cutoff of the amendments to the subsidy scheme in November 2019 and June 2020. Grey shaded areas indicate periods of lockdown due to Covid-19.

Sources: German Federal Motor Transport Authority, ADAC, own calculations



Fig. 4 Market share by county in 2021. Note: The maps show the share of BEV and PHEV registrations of all price segments amongst the total registrations per county in 2021. Sources: German Federal Motor Transport Authority, own calculations

4 Research Design

4.1 Synthetic Control Method

The aim of the empirical analysis is to identify the effect of purchase subsidies on registrations per 100,000 inhabitants of eligible BEVs and PHEVs, respectively. We propose two approaches. First, we run a synthetic control estimation at the country level to obtain a baseline average treatment effect following the literature (Abadie and Gardeazabal 2003; Abadie 2021). Specifically, we estimate the effect of subsidies on electric vehicle take-up in Germany by comparing observed registrations in Germany with estimated registrations for a synthetic Germany constructed by using registrations from a potential donor pool of European countries. Registration data for donor pool countries is provided by the European Alternative Fuels Observatory (EAFO) of the European Commission and includes total BEV and PHEV registrations at the national level for all European countries and every month throughout our sample period.⁹

The potential donor pool consists of the German neighbours Belgium, Denmark, France, Luxembourg, Austria, Sweden and Switzerland.¹⁰ Following common practice in the synthetic control literature, we restrict the donor pool to countries that ex-ante can be considered good control units and thereby decrease the risk of over-fitting (Abadie 2021).¹¹ Several

⁹Note that registrations in donor pool countries reflect new vehicle registrations and do not take into account used vehicle registrations. This feature of our dataset eliminates the concern for potential spillover effects (e.g. through German EVs and PHEVs being exported to neighbouring countries after receiving the subsidy) that could invalidate our identification strategy.

¹⁰We exclude registrations from the Netherlands, as they follow a registration pattern that is unique amongst European countries: registration numbers for both BEVs and PHEVs concentrate in the month of December and are very low for the remaining months of the year.

¹¹Including all European countries in the EAFO dataset as donor pool countries would most likely yield estimates that are biased upwards, as electric mobility in a range of countries in Southern and Eastern Europe

countries have some form of policy support for the uptake of electric vehicles, including the countries in the donor pool. We discuss how this impacts our estimates and present a range of robustness tests in Sect. 4.3. The pre-intervention period contains the months from January 2015 up to October 2019, after which newly registered vehicles became eligible for large subsidies. As a robustness check, we use a shorter pre-intervention period up until October 2018. In addition to allowing us to identify any anticipation effects, this backdating approach can also be regarded as an in-time placebo test ensuring that both Germany and the synthetic counterfactual behave similarly until the treatment period (Abadie et al. 2015). The treatment effect is estimated as the difference between observed registrations in Germany and the counterfactual synthetic Germany, which is based on a weighted average of registrations in donor countries. The procedure involves applying the Nelder-Mead (NM) and Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithms to minimise the loss function, usually the mean squared prediction error (MSPE), i.e. the sum of squared residuals between treated and the synthetic control unit. The resulting optimal weights minimise this loss function for the defined pre-intervention period. Therefore, these weights will differ depending on the outcome (EV or PHEV) and the length of the pre-intervention period.

The synthetic control strategy provides an estimate of the average effect of German subsidies, with the counterfactual constructed in a data-driven manner. It also sets the stage for our analysis of heterogeneous effects by providing a sanity check of the empirical strategy used there. Pursuing a synthetic control approach in our analysis of heterogeneous policy effects is not feasible, as no appropriate comparison data are available to us at the same disaggregated level.

4.2 Linear Model with De-trended Registration Data

As a robustness check for our estimation of baseline effects and as the main empirical strategy for our analysis of heterogeneous effects, we specify a simple event study as a linear model with time and county-level fixed effects focusing on the registrations of BEVs and PHEVs in price segments that were eligible for the subsidy (all models with a list price of less than 65,000 euro). The results of this approach would only be informative about the effectiveness of the subsidy in the absence of time-varying confounders that would have also impacted registrations in the counterfactual scenario without the German subsidy scheme. However, other European climate policies targeting transport decarbonization might represent such a threat to identification. In particular, in 2020 the stringency of CO_2 emissions standards mandated by the European Union increased substantially. This policy imposes fleet-level carbon intensity limits on all manufacturers, increasing the incentives to introduce new BEV and PHEV models to the European market and lowering purchase prices.

Based on this insight, we refine our identification strategy. Specifically, we build on our synthetic control approach and address the potential threat to identification due to other confounding time specific variation by leveraging the same BEVs and PHEVs registration data from other European countries provided by the European Alternative Fuels Observatory (EAFO). We use this information to construct a control group to approximate a counterfactual evolution of German registrations at the national level in the absence of its subsidy

would likely have developed more slowly than in Germany even in absence of the treatment. When implementing the synthetic control method including all European countries as donor pool countries, we indeed estimate higher ATTs. Results are available upon request.

scheme. Since we observe the registrations of the control group on the national level, we perform a two step procedure. In the first step, we construct the trend in new registrations of the control group countries and, with this information, we de-trend the registrations over time in the German counties. In the second step we use the de-trended data in an event study approach with time and county-level fixed effects focusing on the registrations of BEVs and PHEVs in price segments that were eligible for the subsidy (all models with a list price of less than 65,000 euro).

In more detail, we first normalize the time series by dividing monthly registrations by the average monthly registrations in 2019. In this way, we can compare the evolution of registrations between countries with different market sizes. We construct the counterfactual normalized trend by taking the unweighted average trend of the same neighboring countries used as donor pool countries for our synthetic control identification strategy (specifically, Austria, Belgium, Denmark, France, Luxembourg, Sweden, and Switzerland), as they are likely to be most similar to Germany and, therefore, best capture the evolution of German registrations without a subsidy scheme. Note, even though we do not observe registrations by price segment for other European countries, we consider the trend in total registrations to be a good proxy for the trend in registrations of models below 65,000 euros, as the market share of BEVs and PHEVs models above 65,000 is close to zero and negligible. Figure 5 illustrates this first step by showing the evolution of monthly BEV (5a) and PHEV (5b) registrations in Germany and the sample of neighboring countries normalized to the average monthly registrations in 2019. Normalized registrations for both Germany and the neighboring countries follow a very similar trend before 2020 and are similarly affected by shocks like the Covid-19 related lockdowns. Normalized registrations also increase substantially in other European countries in 2020, as would be expected given the introduction of strict CO_2 emissions standards. However, the increase is stronger in Germany than in the remaining countries. This suggests that the two subsidy increases in November 2019 and June 2020 drove additional demand for BEVs and PHEVs.

In a second step, we take the absolute difference between the original and counterfactual trends (green line in Fig. 5a and 5b). This difference captures the unexplained variation in the German time series that we attribute to the subsidy. To map this unexplained variation into absolute registrations, we interact the monthly differences in trends with the base value of the German observed time series (average monthly registrations in 2019). This allows us to differentiate between monthly total registrations and the monthly registrations attributed to the subsidy program as reflected in Fig. 5c and 5d. The subsidy effect in these figures is simply the differential trend from Fig. 5a and 5b scaled to the German market size.

The baseline estimation for this identification strategy relies on the following event study model:

$$y_{kit} = \sum_{j=-m}^{q} \delta_j T_{z,z=0+j} + \lambda_i + \epsilon_{it}, \qquad (1)$$

In the first alternative, y_{kit} records the total number of registrations of vehicles in price segment k, county i, and month t per 100,000 inhabitants. δ_j is the coefficient of interest, the point estimate on a pre/post indicator T_z , which tracks periods relative to the start of



Fig. 5 Evolution of normalized, total and counterfactual registrations in Germany. Note: Panels (a) and (b) show the evolution of monthly registrations normalized to the average number of monthly registrations in 2019 for Germany and an unweighted average of neighboring countries (Austria, Belgium, Denmark, France, Luxembourg, Sweden, and Switzerland). Panels (c) and (d) show the evolution of total registrations in Germany as well as the total subsidy effect as discussed in the main text. The first dotted line indicates the introduction of the subsidy system in May 2016. The second and third dotted lines show the eligibility cutoff of the amendments to the subsidy scheme in November 2019 and June 2020. Grey shaded areas indicate periods of lockdown due to Covid-19

Sources: European Alternative Fuels Observatory (EAFO), own calculations.

the post-treatment period in May 2016.¹² We estimate δ_j at the trimester frequency, with δ_0 being the coefficient in the first post-treatment trimester, and δ_m and δ_q the earliest pre-treatment and latest post-treatment trimester, respectively. Our current dataset contains five pre-treatment trimesters and 23 post-treatment trimesters. Estimates of δ_j for the pre-treatment periods capture anticipation effects, while δ_j in the post-treatment period estimate the policy's effectiveness. We further include county fixed effects λ_i and cluster standard errors at the region (*Bundesland*) level. In the second alternative, the outcome y_{kit} is not based on total number of registrations but on the de-trended number of registrations. As mentioned above, each county by price segment time series is de-trended based on the trend of neighboring countries presented in Fig. 5.

In order to move beyond the mean effect and to analyze the heterogeneity of the subsidy across different subsamples, we develop Eq. 1 by aggregating the time variation and introducing group-specific interactions:

¹²Since the pre-trend in levels is very similar between the treatment and the control group we specify the estimation equation in levels instead of using a log specification.

$$y_{kit} = \sum_{j=0}^{2} \delta_j T_j + \sum_{j=0}^{2} \sum_{d=2}^{4} \delta_{jd} (T_j \times H_d) + \lambda_i + \epsilon_{it},$$
(2)

Equation 2 is defined similarly to Eq. 1. The time grouping indicators are aggregated so that we distinguish between the "No policy" period (j=0), the "Reform 1" period (j=1), and the "Reform 2" period (j=2). This specification additionally includes an interaction term between the time grouping indicator T_j and a subsample indicator H_d . As mentioned in Sect. 3.1, subsamples of interest are defined along three different dimensions of heterogeneity at the regional level: mean household income level in 2019, share of votes for the Green Party in the 2017 German Federal elections, and population density. For each heterogeneity analysis of interest, we split our 399 counties into four groups of equal size. The indicator H_4 is equal to 1 if county *i* belongs to the 100 counties with higher values of, for instance, average household income and 0 otherwise. H_3 is equal to 1 for counties above the median but below the 75th percentile and H_2 is equal to 1 for counties below the median but above the 25th percentile.

4.3 Threats to Identification

Threats to identification arise from two main sources: concurrent policies i) in Germany and ii) in countries of the comparison group. As the number of vehicle registrations reacts immediately and strongly to the increased purchase subsidy payments of Reform 2, the threat to identification only stems from other policies that were introduced at the same time. While the concurrent introduction of other support policies in Germany would tend to bias the impact of purchase subsidies upwards, the introduction of support policies in other countries would introduce a downward bias to our analysis. In addition, it is important to highlight that the results of our identification strategies must be interpreted in the context of the policy package that we evaluate. For instance, the causal effects of the BEV subsidy on BEV uptake might have been different in the absence of the subsidy for PHEV and vice versa. We acknowledge this policy interaction and see all our results as specific to the policy context at hand.

In the following we document the existence of additional policy measures in Germany and national support policies in comparison countries during the relevant period. In addition, we describe a series of robustness checks, the results of which are presented in Sect. 5 and remain in line with our main results.

4.3.1 Concurrent Introduction of Other Support Policies in Germany

Table 7 presents an overview of support policies for electric vehicles in Germany at the federal, state and county levels during our sample period. At the federal level, the main incentives, other than purchase subsidies, included grants and loans for expanding public and private charging infrastructure and an exemption from the vehicle registration tax. However, the only measure introduced concurrently to the increase in purchase subsidies was a loan program by *Kreditanstalt für Wiederaufbau (KfW)*, a government-owned development bank, aimed at supporting mid-size companies in financing climate protection measures— including the acquisition of electric vehicles. The funding from this program was

conditional on fulfilling additional criteria with respect to low-carbon heat and electricity, so that we do not expect major direct effects on the uptake of EVs. Other policies at the federal level were put in place well before or after the expansion of the purchase subsidy program.

A number of states also offered support programs for electric mobility, mostly for charging infrastructure. The majority of these were initiated either well before the change in the level of purchase subsidies (Berlin, Northrhein-Westphalia) or afterwards (Baden-Württemberg). Only programs supporting the purchase of non-public charging infrastructure in the state of Schleswig-Holstein were introduced at the same time.

Finally, a number of incentives for EVs were introduced at the municipal level. These measures primarily focused on privileged access to public space, mostly by allowing EVs to use bus lanes and by allowing free parking while charging or in general. The legal basis for these privileges is the 2015 Electric Mobility Law (BMDV 2015) and the vast majority of local incentives were introduced well before the increase in purchase subsidies. Exceptions are cities like Munich and Bad Segeberg, which provided concurrent local grants for charging infrastructure and EV purchase.

Based on our presentation of other support policies in Germany we acknowledge the potential for a bias in the direction of exaggerating the impact of the purchase subsidies due to the concurrent introduction of other support policies. However, in robustness checks in which we exclude affected regions and cities such as Schleswig-Hosltein, Munich and Bad Segeberg we can show that results do not significantly change.¹³

4.3.2 Concurrent Introduction of Other Support Policies in Comparison Countries

In contrast to local concurrent policies in Germany, policy incentives for electric mobility in countries of the donor pool would bias our estimates downwards. In Table 8 we document changes to these policies in the donor pool countries during the relevant time period comprising the years 2019 to 2021. We focus on financial incentives at the time of purchase, as they are likely to be more salient than future financial savings or non-monetary incentives. We thus differentiate between subsidy schemes at the national level and (registration) tax incentives at the national or local level.

Regarding subsidy schemes, it is important to note that the majority of donor pool countries did not have or did not change their subsidy schemes during the relevant time period. In more detail, Austria maintained the level of their subsidy constant between 2019 and 2021 and Belgium, Denmark and Switzerland did not have any national subsidy scheme for electric mobility.¹⁴ In contrast, three countries had (mostly mild) increases in their subsidy policies. France increased the maximum premium of its feebate system for BEVs from 6,000 euro to 7,000 euro in 2021. Luxembourg increased the subsidy for BEVs from 5,000 euro to 8,000 euro in 2021 while at the same time decreasing the subsidy for PHEVs by 1,000 euro. Finally, Sweden increased the subsidy to BEVs by SEK 10,000 and adjusted the subsidy for PHEVs in 2021.

¹³ Results are available upon request.

¹⁴Some mobility policies in Switzerland are decided at the cantonal level, including subsidy schemes for BEVs and PHEVs. Three cantons offered BEV subsidies throughout the relevant time period and only two (Schaffhausen and Valais) started doing so in 2021. We argue that these two cantons are not populated enough to noticeably affect registrations at the national level.

In the case of tax incentives at acquisition, one should bear in mind that the size of financial incentives is in general considerably smaller than that provided by subsidies. We presume that most of the recorded changes, such as a reduction in the registration tax in Luxembourg in 2021 or the end of a PHEV tax exemption in Flanders (Belgium) in 2020, do not meaningfully impact registrations at national level. One noteworthy exemption is Denmark, which redesigned the tax incentives around vehicle registration in 2021 in order to substantially increase support for BEVs and PHEVs.

The donor pool of our main results includes all the countries mentioned in Sect. 4.1, as we face a trade-off between allowing more flexibility in the pre-treatment fit and potentially biasing our results by including countries with (mostly minor) changes to their electric mobility incentive schemes. However, we perform two sets of additional robustness tests and show that the main results do not change when restricting the donor pool to countries without policy change. First, we present additional synthetic control results changing the underlying set of donor pool countries to exclude countries with changes to their national subsidy schemes (France for BEVs, Luxembourg, Sweden) and important tax reforms (Denmark) (see Fig. 9). Second, in the context of our linear model we perform leave-one-out tests for each country and we completely exclude France from the set of control countries (see Fig. 10).¹⁵ Results remain in line with our main results for all these different specifications.

5 Results

Section 5.1 presents baseline results for the average effect of the German subsidy scheme on the uptake of BEVs and PHEVs, respectively, using a synthetic control strategy. Section 5.2 shows very similar results based on the linear model. In Sect. 5.3, we then consider the distributional impact of the subsidy by studying the program's heterogeneous effects along several relevant dimensions. Finally, based on the empirical results, we calculate in Sect. 5.4 the environmental effectiveness of the subsidies for BEVs and PHEVs.

5.1 Synthetic Control Method

We first perform an estimation of baseline effects using a synthetic control approach, for BEVs and PHEVs, respectively. The algorithm assigns weights to the potential donor countries as shown in Table 9. For BEVs, Belgium receives the largest weight with 0.73, followed by Denmark (0.11) and France (0.08). For PHEVs, France receives the largest weight (0.57), followed by Austria (0.11) and Denmark (0.09).

Figure 6 presents the main results for the synthetic control approach.¹⁶ Panel 6a shows a tight match in the period before the subsidy increase between BEV registrations in the observed and synthetic Germany. This is confirmed by considering the difference between the two time series (Fig. 6c), which also shows a clear increase in observed German BEV registrations after the implementation of the reforms, compared to registrations in the synthetic Germany. The estimated average treatment effect on the treated of 9.75 for the period

¹⁵We exclude France in some robustness tests due to the potential interplay between subsidies for electric mobility and the domestic automotive industry in that country.

¹⁶Due to the small set of donor pool countries we choose not to perform inference tests in the context of synthetic control estimation.



(a) BEV - Germany vs. Synthetic Germany

(b) PHEV - Germany vs. Synthetic Germany



(c) BEV - Difference observable vs. synthetic

(d) PHEV - Difference observable vs. synthetic

Fig. 6 Evolution of observed and synthetic Germany over time. Note: This figure presents the main results of our synthetic control estimation. (**a**) and (**b**) present the evolution of registrations per 100.000 inhabitants in Germany and the synthetic counterfactual for BEVs and PHEVs, respectively. (**c**) and (**d**) visualize the difference between treatment and synthetic control. The dotted line represents the first increase of the subsidy in October 2019. The resulting ATTs after October 2019 are 9.75 BEV registrations per 100.000 inhabitants and 5.46 PHEV registrations per 100.000 inhabitants. Weights are assigned to the set of donor countries as presented in Table 9

Sources: European Alternative Fuels Observatory (EAFO), own calculations

after October 2019 suggests that the introduction of large subsidies led to an increase in monthly BEV registrations by almost 10 vehicles per 100,000 inhabitants and that this increase was particularly strong after the second subsidy increase in June 2020. The effect magnitude is very similar to our results using the linear model (see Table 3 in the following Sect. 5.2).

For PHEVs, the synthetic Germany constructed from donor pool countries also closely matches observed German PHEV registrations (Fig. 6b). Figure 6d also shows a significant increase in observed compared to counterfactual registrations, although of smaller magnitude than for BEVs. The estimated ATT for the period after October 2019 is 5.46, suggesting

	BEVs		PHEVs		
	(1)	(2)	(3)	(4)	
	<65	<40	<65	<40	
Reform 1	0.81***	0.81***	-0.09	-0.05	
	(0.10)	(0.10)	(0.13)	(0.14)	
Reform 2	10.41***	9.83***	6.49***	5.51***	
	(1.68)	(1.72)	(0.61)	(0.49)	
County FE	Yes	Yes	Yes	Yes	
Ν	34314	34314	34314	34314	
Pre-Reform Mean	0.71	0.71	0.93	0.89	

Table 3 Main results

Estimated coefficients based on Eq. 1 estimated on detrended data separately for BEVs registrations (columns 1-2) and PHEV registrations (columns 3-4). Registrations include all models below 65,000 euro (columns 1 and 3) and only models below 40,000 euro (columns 2 and 4). The coefficient Reform 1 refers to the time period May 2016 - Oct 2019 and Reform 2 to the time period Nov 2019 - Feb 2022. Coefficients have to be interpreted with respect to the pre-reform period (Jan 2015 - April 2016) and represent the average change in registrations per 100,000 inhabitants. Standard errors clustered at the regional level (Bundesland) in parenthesis. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

that the introduction of generous subsidies caused an increase in PHEVs by more than five vehicles per 100,000 inhabitants. This estimate is somewhat smaller yet still in line with results based on the linear model (see Table 3).

In Fig. 8 we provide a set of robustness results for our synthetic control estimation. Figure 8a and Fig. 8b show graphical results for BEVs and PHEVs, respectively, based on a shorter pre-treatment period from January 2015 until October 2018. The resulting ATTs are 8.38 additional BEV registrations per 100.000 inhabitants and 4.38 additional PHEV registrations per 100.000 inhabitants. These are smaller but still similar in magnitude compared to the results from our main synthetic control specification and the linear model. Moreover, Fig. 9 presents additional robustness results excluding countries with concurrent subsidy schemes as discussed in Sect. 4.3. Figure 9a and 9c show that excluding countries with changed (9,45 per 100.000 inhabitants for BEVs and 4,73 per 100.000 inhabitants for PHEVs). Excluding Denmark in addition to these countries increases our point estimate, but they remain in line with our main findings.

5.2 Linear Model

Figure 7 shows point estimates and 95% confidence intervals for our estimates of the German subsidy scheme's average effectiveness using Eq. 1. Figure 7a shows results for BEVs, while Fig. 7b contains the analogous results for PHEVs. For each of the two market segments, we present results using only the times series for Germany (Approach 1) and using the de-trended data for Germany (Approach 2), as outlined in Sect. 4.2.

In both cases, point estimates prior to the introduction of the subsidy scheme in May 2016 are close to zero and not significant. After the introduction of the reform, the results of the two approaches strongly differ. This demonstrates the importance of accounting for concurrent confounding time trends and policy changes at the European level. Using the German data only (dashed lines in Fig. 7a), we estimate that the subsidy scheme caused



Fig. 7 Subsidy effect over time. Note: Regression results based on Eq. 1 estimated on the observed (dashed lines) and detrended (cont. line) data. Confidence intervals are based on standard errors clustered at the regional level (Bundesland). The first dotted line indicates the introduction of the subsidy system in May 2016. The second and third dotted lines show the eligibility cutoff of the amendments of the subsidy scheme in November 2019 and June 2020

increases in the uptake of BEVs in 2016 already, with effects strengthening progressively to about 5 additional registrations per 100,000 inhabitants and month after the first increase in the amount paid after November 2019. Effects escalate after the second increase in per-unit subsidy amounts in mid-2020 to more than 30 units registered per 100,000 inhabitants and month.

When accounting for other time variation, including the EU CO_2 standards (continuous lines in Fig. 7a), the effects are markedly lower. Point estimates are much closer to zero between the introduction of the subsidy scheme in mid-2016 and prior to the second increase in mid-2020 and are rarely statistically significant. However, even with the detrended data, we find significant and positive effects after the introduction of the more generous subsidies. Subsidies lead to an increase in BEV registrations of about 10 registrations per 100,000 inhabitants. The effect for PHEVs is of slightly lower magnitude (Fig. 7b). In the following, given the importance of the confounding time variation, we focus only on the de-trended analysis.

In Table 3, we focus on the average effects of the different policy reforms. Specifically, we estimate Eq. 1, but instead of deriving quarterly effects, we estimate the effect of the reform periods defined in Table 1, Reform 1 (2016-2019) and Reform 2 (2019-2022)– on the number of registrations. The results for BEVs (Table 3, columns (1) and (2)) confirm the findings of the more disaggregated analysis. The first reform, which introduced modest subsidy levels (see Table 1), had a small but significant effect on registrations of BEVs. We find that the introduction of purchase subsidies increased monthly registrations of BEVs by 0.81 vehicles per 100,000 inhabitants¹⁷ in each county and month, which represents an increase of 115% compared to the average number of registrations per month during the pre-reform period. The magnitude of the coefficient for the first reform stage is unchanged, no matter whether we only consider the sample of BEVs with listed prices of up to 40,000 euro or also include vehicles with prices up to 65,000 euro. The effect of the second reform stage, with much-increased subsidy payments, is much larger, at about 10 registrations per month, or about 1400% compared to the pre-treatment period. Again, the effects are broadly similar irrespective of the sample choice.

Assuming full pass-through of purchase subsidies,¹⁸ the elasticity implied by the coefficient estimate for Reform 2 in Table 3, Column (1) is approximately 3.16% in absolute terms, meaning that for a one percent increase in the subsidy BEV registrations increase by about 3.16%.¹⁹ Our estimate of the elasticity is toward the upper end of the range provided in Muehlegger and Rapson (2022), who estimate, again in absolute terms, a lower bound of 0.3-0.9 and an upper bound of 2.8-3.8, with preferred estimates in the range 2.1-2.2. A higher uptake of the subsidy in our setting may be explained due to the focus of the subsidy scheme in Muehlegger and Rapson (2022) on low- and middle-income consumers, whereas

¹⁹The implied elasticity is calculated as follows: Purchase subsidies increase by $\frac{6,000-2,000}{2,000} = 200\%$ from

Reform 1 to Reform 2. Registrations in Reform 2 compared to Reform 1 increase by $\frac{10.41-0.81}{1.52} = 632\%$. The implied elasticity is approximately $\frac{632}{200} = 3.16$. Implied elasticities for the other point estimates in Table 3 can be computed analogously.

¹⁷As all registration numbers are normalized by population and all point estimates represent registrations per 100,000 inhabitants, for shortness we henceforth omit the reference to population-normalization when interpreting coefficients

¹⁸Barwick et al. (2023) show that for vehicle models sold in more than 11 countries full pass-through cannot be rejected.

in our setting the subsidy is unrestricted with respect to socio-economic characteristics. Therefore, it might be that high-income buyers are more able to afford the still relatively high post-subsidy prices of new EVs during our sample period. Nevertheless, again as in Muehlegger and Rapson (2022), due to the small baseline quantity the considerable elasticity translates into moderate additional numbers of new vehicles.

The effects for PHEVs are much smaller and only significant for the second reform stage (Table 3, columns (3) and (4)). We estimate that subsidies for PHEV purchases resulted in additional PHEV registrations of 6.49 (all eligible vehicles) and 5.51 (vehicles below 40,000 euro) per month. This implies an increase in eligible PHEV registrations of 600% compared to the pre-treatment period. The comparison of all price segments that received the subsidy (vehicles with listed prices of less than 65,000 euro) with the sample of vehicles with listed prices below 40,000 euro shows again that the overall effect and the effect for vehicles below 40,000 euros hardly differ.²⁰ The similarity of results for BEVs irrespective of whether or not we include the price segment of 40,000-65,000 euro reflects the large share of the segment under 40,000 euro in the BEV market (see Fig. 3a). The point estimates for PHEVs for Reform 2 differ a little more, also in line with the larger share of mid-segment PHEVs (see Fig. 3b).

For BEVs, the point estimate for the effect of Reform 2 is an order of magnitude larger than the statistically significant but economically insignificant coefficient for Reform 1. For PHEVs, the coefficient for Reform 1 is both statistically and economically insignificant. This increase of the effectiveness of purchase subsidies between the two reforms is explained by a combination of treatment intensity and treatment heterogeneity. First, the treatment intensity increased substantially, with a rise in the government share of the subsidy from 2,000 euro in Reform 1 to 6,000 euro in Reform 2, an increase by 200%. Second, as in any causal analysis, internally valid causal estimates are still a function of the context in which they occur. In this case, the higher subsidy met a market with more models on offer. While disentangling the relative importance of these forces is beyond the scope of this paper, addressing this issue would be a fruitful avenue for future research.

As discussed in Sect. 4.3, we additionally present results following a leave-one-out strategy. Note that our results are robust to alternative compositions of the control group. Figure 10 shows estimates of the coefficient of the "Reform 2" stage for the price segment of vehicles below 65,000 euro for different compositions of the control group.²¹

Finally, we replicate the previous results but focus on the outcome of absolute total registrations per county instead of normalized registration per 100,000 inhabitants. In contrast to the coefficients based on the normalized specification, these coefficients can be aggregated across counties into a total subsidy effect. Thus, this specification will become relevant for the calculations on environmental effectiveness in Sect. 5.4. Table 4 presents the results analogously to Table 3. Starting from an average of two registrations per month and county during the pre-treatment period, the increase in absolute registrations amounts to 20.7 (BEV) and 11.8 (PHEV) additional registrations per month and county during the Reform 2 period.

²⁰Note that our results in Column 1 and 3 are not driven by strategic pricing adjustments by car manufacturers, as we exclude from our analysis all models that change their pricing around the 65,000 euro threshold. The fact that the estimates based on the <40,000 euro threshold are very similar suggests that strategic pricing is also not playing a major role in these results.

²¹Results are qualitatively similar for the other coefficients presented in Table 3 and are available upon request.

	BEVs		PHEVs	
	(1)	(2)	(3)	(4)
	<65	<40	<65	<40
Reform 1	1.46***	1.46***	-0.38	-0.29
	(0.30)	(0.31)	(0.24)	(0.22)
Reform 2	20.70***	19.26***	11.84***	10.55***
	(4.13)	(4.01)	(3.45)	(2.89)
County FE	Yes	Yes	Yes	Yes
N	34314	34314	34314	34314
Pre-Reform Mean	2.0	2.0	2.0	1.9

Table 4 Main results - absolute detrended registrations

Estimated coefficients based on Eq. 1 but estimated without population normalization separately for BEVs registrations (columns 1-2) and PHEV registrations (columns 3-4). Registrations include all models below 65,000 euro (columns 1 and 3) and only models below 40,000 euro (columns 2 and 4). The coefficient Reform 1 refers to the time period May 2016 - Oct 2019 and Reform 2 to the time period Nov 2019 - Feb 2022. Coefficients have to be interpreted with respect to the pre-reform period (Jan 2015 - April 2016) and represent the average change in registrations. Standard errors clustered at the regional level (Bundesland) in parenthesis. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5.3 Heterogeneous Effects

So far, we have focused on average effects of the policy reforms. In this section we turn to the estimation of Eq. 2 to test if the effects vary between regions in a systematic way. Specifically, we rank the regions by income, voting shares for the Green Party, and population density, and defining groups according to quartiles of the respective variables. As base category, we define regions in the lowest quartile. Thus the point estimates refer to δ_{jd} in Eq. 2 and are interpreted as the difference in registrations per 100,000 inhabitants relative to the base category.

In Table 5, we show results for the registrations of BEVs (columns 1-3) and PHEVs (columns 4-6). For BEVs, registrations strongly vary with household income, averaged at the county level, and differ by reform stage (Table 5, column (1)). For the first reform, statistically significant heterogeneity is only present for regions in the top income quartile: we find that registrations increase by 0.55 for counties in the top quartile of the income distribution. For the second reform stage, the differences between income groups are much more pronounced. The baseline effect of the reform, which measures the effect for regions in the first quartile, is statistically not different from zero, i.e. we estimate that demand for BEV in low-income counties does not react to the purchase subsidy. However, already for regions in the second quartile point estimates are markedly higher and significant, suggesting that registrations increase by 8.72 per month for counties in the second quartile of the countylevel income distribution, compared to the baseline category. This effect further increases for higher quartiles. Our estimates suggest that registrations in regions in the highest income quartile increase by more than 10 per 100,000 inhabitants relative to regions in the lowest quartile. A higher subsidy uptake in higher-income regions is in line with Borenstein and Davis (2024), who show that in the U.S. tax incentives for EV purchases are disproportionately captured by higher-income households. Our results are also in line with the evidence presented by Bigler and Radulescu (2022), who find that in Switzerland demand for EVs is positively related to income. For PHEVs, there is no clear evidence of heterogeneity during the Reform 1 period. Regarding Reform 2 and in contrast to BEVs, we observe a positive

	BEV			PHEV		
	(1)	(2)	(3)	(4)	(5)	(6)
	HH income	Green party	Pop. density	HH income	Green party	Pop. density
Reform 1	0.66***	0.51***	0.62***	0.09	0.08*	-0.11
	(0.09)	(0.05)	(0.10)	(0.06)	(0.04)	(0.17)
Reform 2	3.18	8.12***	10.39***	4.84***	4.70***	4.86***
	(4.28)	(0.87)	(1.00)	(0.51)	(0.56)	(0.49)
Reform 1 x 2nd Q	-0.06	0.21**	0.26***	-0.16*	0.17	0.23
	(0.12)	(0.09)	(0.08)	(0.08)	(0.18)	(0.18)
Reform 1 x 3rd Q	0.10	0.49***	0.32***	-0.61	-0.57	0.21
	(0.16)	(0.11)	(0.11)	(0.42)	(0.43)	(0.25)
Reform 1 x 4th Q	0.55***	0.49*	0.15	0.06	-0.25**	-0.36*
	(0.13)	(0.23)	(0.17)	(0.21)	(0.10)	(0.18)
Reform 2 x 2nd Q	8.78*	5.74***	1.60*	1.33*	4.16**	1.32
	(4.22)	(1.54)	(0.77)	(0.64)	(1.54)	(0.81)
Reform 2 x 3rd Q	9.58**	-0.39	3.55**	2.07**	1.78**	3.32
	(4.33)	(4.63)	(1.29)	(0.71)	(0.78)	(1.98)
Reform 2 x 4th Q	10.57**	3.85**	-5.07	3.16	1.22	1.87**
	(4.63)	(1.40)	(4.57)	(2.90)	(1.28)	(0.69)
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Ν	34314	34314	34314	34314	34314	34314

Table 5 Heterogeneous effects of the consumer subsidy

All results based on detrended data of registrations of models below 65,000 euro. All columns are based on Eq. 2. Baseline coefficients represent the effect of the two reforms (Reform 1 and Reform 2) on the lowest quartile. Interacted coefficients represent the effect of one of the two reforms in counties belonging to one of the three other quartiles of the respective distribution (Quartile 2, Quartile 3, Quartile 4). Coefficients are interpreted as average change in registrations per 100,000 inhabitants. Standard errors clustered at the regional level (Bundesland) in parenthesis. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

subsidy effect already in the counties belonging to the first income quartile. As with BEVs, the point estimates become larger with higher county-level income, although differences by quartile are less extreme than for BEVs and the estimate for the richest counties (quartile 4) is not statistically significant.

We also find heterogeneous effects in the other two dimensions, although baseline effects for BEVs are much higher and always significant, while differential effects in different quartiles are less pronounced. For BEVs, the policy effect is stronger in regions with a high share of votes for the Green Party, our proxy of pro-environmental attitudes. The baseline effect is strongly significant and, in the second reform stage, it is economically large, at about 8 registrations per month (Table 5, column (2)). The 25% "greenest" counties account for an additional 3.85 registrations per month, about one third of the magnitude found for richest counties. Our result that uptake of the subsidy is greater in greener counties is in line with results by Sexton and Sexton (2014). In combination, these results showing that higher-income and "greener" counties drive the uptake of BEVs is consistent with the existing evidence (e.g. Allcott et al. 2015). Patterns with respect to our greenness proxy for PHEVs are similar to those for income. The baseline effects are almost identical, at 4.7 registrations per month. Registrations increase in "greener" counties, except for the quartile of particularly green counties, where we do not observe a significant policy effect on the registrations of PHEVs.

Population density also matters for the uptake of BEVs, with patterns showing some similarity to our proxy for pro-environmental attitudes. The baseline effect is high, at 10.39 registrations per county and month (Table 5, column (2)). Policy effects tend to be stronger in more densely populated counties, presumably areas with shorter commutes and a denser charging network. Interestingly, according to our estimates, the effect of the subsidy in the most densely populated regions is not different from the effects in the least populated regions, while additional registrations are peaking in the third quartile, with an additional 3.55 registrations per county and month. This result suggests that the uptake of BEVs is driven by sub-urban areas rather than metropolitan centers. With respect to "range anxiety", this evidence suggests that BEVs are preferred in less rural counties with more charging options and shorter trips, with the exception of highly urbanized counties, where other forces- possibly the higher opportunity cost of owning vehicles and more viable transportation alternatives- appear to be counteracting it. Overall, in our setting, range and charging concerns, as proxied by population density, do not seem to be a strong driver of the reaction to BEV subsidies, at least compared to income and environmental attitudes. Of course, in a generally densely populated country like Germany, such concerns are likely to be muted compared to a setting like the U.S. Regarding PHEVs, we only observe a statistically significant additional subsidy effect in the most densely populated counties. With an increase of 1.87 additional PHEV registrations per 100,000 inhabitants, this pattern is qualitatively opposite to the results for BEVs.

5.4 Environmental Effectiveness

In the final section, we use the empirical results to calculate the environmental effectiveness of the subsidy scheme, similar to Chen et al. (2021). We place a particular emphasis on comparing relative effectiveness between BEVs and PHEVs as well as on calculating abatement costs per tonne of CO_2 abated in the second reform period between November 2019 and February 2022, the period with high per-unit subsidy payments. We proceed in four steps. Table 6 presents an overview of these calculations.

First, we calculate the amount of public funds (i.e. disregarding the manufacturer share of the subsidy payments) spent on the subsidy program between November 2019 and February 2022. Combining our data on registrations by vehicle price segment with the different subsidy amounts available over time, we arrive at a total sum of 3.2 billion euros for BEVs (3.4 billion USD; 23.6 billion Chinese Yuan) and 2.2 billion euros for PHEVs (2.3 billion USD; 16.2 billion Chinese Yuan). Note that this first step assumes every eligible vehicle's owner actually applied for the subsidy.

In a second step, we quantify the difference between actual and counterfactual (or inframarginal) BEV/PHEV uptakes, i.e. how many registrations would not have occurred without the subsidy scheme. Note that we cannot directly scale the causal effects reported in Table 3 into total marginal registrations due to the population normalization. Therefore, in Table 4, we replicate the results shown in Table 3 using unweighted registrations. We can now scale the coefficients in monthly absolute levels reported in Table 4 of 20.7 (BEVs) and 11.84 (PHEVs) to 399 counties and multiply the result by the number of months over the Reform 2 period (28 months). We end up attributing a total of 231,260 BEV registrations and 132,276 PHEV registrations to the subsidy. Consistent with the evidence reported in Fig. 7, we document that a large share of BEV and PHEV registrations were not induced by Table 6 Overview of al cost calculation

Iable 6 Overview of abatement		BEV	PHEV
cost calculation	Input parameters		
	Additionality of subsidy scheme		
	Total registrations	559,899	531,431
	Total subsidy amount (mill. euro)	3,216	2,180
	Subsidy causal effect (regs./county-month)	20.70	11.84
	Subsidy-induced registrations	231,260	132,276
	Share of marginal registrations (%)	41.3	24.9
	Purchase grant per induced registration	13,908	16,486
	Parameters on environmental effectiveness		
	Average electric. consumption (kWh/100km)	14.3	14.5
	Average tailpipe emissions (kg CO_2 /100km)	NA	3.93
	Average total emissions (kg CO_2 /100km)	6.01	10.02
	Average ICE emissions (kg CO_2 /100km)	12.87	
	Top20% ICE emissions (kg CO_2 /100km)	11,12	
	Electricity CO_2 intensity (g CO_2 /kWh)	420	
	Yearly distance driven (km)	13,000	
	Distance with BEV/PHEV if range anxiety (km)	9,750	
All calculations based on the	Years until scrappage	18	
November 2019 - February 2022 period (Reform 2	Abatement results		
period). Subsidy causal effect	Scenario 1: Average ICE and no range anxiety		
taken from Table 4. Average	Total abatement per vehicle (CO_2 tonnes)	16.06	6.68
electricity consumption and	Abatement cost (euro/ CO_2 tonne)	866	2,468
based on ADAC data for the	Scenario 2: Top 20% ICE and no range anxiety		
Reform 2 period. We take the	Total abatement per vehicle (CO_2 tonnes)	11.97	2.59
estimate of the German power $arid CO_{2}$ intensity from the	Abatement cost (euro/ CO_2 tonne)	1,162	6,376
German Environmental Office	Scenario 3: Average ICE and range anxiety		
for the year 2021 (available	Total abatement per vehicle (CO_2 tonnes)	12.05	5.01
here). Yearly distance driven is taken from calculations by	Abatement cost (euro/ CO_2 tonne)	1,155	3,290
the German Federal Transport	Scenario 4: Top 20% ICE and range anxiety		
authority (available here), while	Total abatement per vehicle (CO_2 tonnes)	8.98	1.94
years until scrappage are taken from Held et al. (2021).	Abatement cost (euro/ CO_2 tonne)	1,550	8,501

the subsidy program and would have also occurred in the absence of the policy. According to our analysis, 59% of the observed BEV registrations and 75% of the observed PHEV registrations were non-additional. The effectiveness of the German subsidy scheme is somewhat lower than in Li et al. (2022), who find that subsidies explain about half of EV purchases in China. The implied subsidy per induced registration is higher than the nominal subsidy per vehicle of the subsidy scheme: the subsidy per additional registration amounts to around 14,000 euro for BEVs and 16,500 euro for PHEVs. These implied subsidies per induced registration are in line with the calculation by Rapson and Muehlegger (2023) for the case of medium demand elasticity and non-Tesla BEVs.

In a third step, we approximate the CO_2 abatement of newly registered BEVs and PHEVs, respectively. We calculate abatement in four different scenarios. First, we assume that both BEVs and PHEVs replace the purchase of an internal combustion engine (ICE) vehicle with either average fuel efficiency or the fuel efficiency of the first quintile of the ICE fuel efficiency distribution. The latter choice allows us to take into account the fact that purchasers of BEVs and PHEVs might have purchased particularly efficient ICEs otherwise, as shown in Xing et al. (2021). In addition, we assume that purchasers drive 13,000 km per year²² for 18 years (following Held et al. (2021)).²³ However, in order to reflect the potential for range anxiety, we distinguish the cases where the new owner exclusively drives the new BEV/PHEV and cases where the owner only drives the new BEV/PHEV for 75% of the total yearly distance, while the remaining distance is driven by an ICE of average or above-average fuel efficiency. The latter scenario allows us to model purchasers that might rent or own a second ICE vehicle and use it for trips in which they fear a lack of charging infrastructure. According to the information at the vehicle model level provided by ADAC, the average CO₂ emissions of an ICE vehicle over the second reform period in our dataset amount to $12.87 \text{ kgCO}_2/100 \text{km}$. The equivalent emissions of an ICE at the 20th percentile of the fuel efficiency distribution is $11.12 \text{ kgCO}_2/100 \text{km}$. For the same period, the average BEV consumes 14.3 kWh/100km, which given the average carbon intensity of the German power sector of 420 gCO₂/kWh amounts to 6 kgCO₂/100km.²⁴ For PHEVs, we combine the average direct CO_2 emissions of 3.93 kg $CO_2/100$ km with the emissions resulting from an average consumption of 14.5 kWh/100km. Altogether, the emissions from an average PHEV during the second reform period amount to $10 \text{ kgCO}_2/100 \text{km}$.

The bottom half of Table 6 presents the resulting total CO_2 abatement over the course of 18 years for the four different scenarios that we consider. In addition, it shows abatement costs estimates for the BEV subsidy and PHEV subsidy scheme. In a scenario with no range anxiety and where purchases replace an ICE of average fuel efficiency (Scenario 1), an average BEV would abate 16.06 tonnes of CO_2 , while an average PHEV would abate 6.68 tonnes of CO_2 . The BEV subsidy scheme would imply abatement costs of 866 euro per tonne of CO_2 , while the PHEV subsidy scheme would imply 2,468 euro per tonne of CO_2 . If the replaced purchase was an efficient ICE (Scenario 2), the estimated abatement costs increase slightly for BEV to 1,162 euro per tonne of CO2 and increase sharply for PHEV to 6,376 euro per tonne of CO_2 . This latter stark increase arises as the total emissions of an average PHEV are only slightly below those of the efficient counterfactual ICE. In Scenario 3, we assume again a counterfactual ICE purchase of average fuel efficiency but allow for range anxiety. Compared to Scenario 1, total abatement of an average BEV decreases and the resulting abatement cost is similar to the one of Scenario 2. Scenario 4 combines both an efficient counterfactual ICE purchase and range anxiety. Total BEV abatement decreases by around 50% compared to Scenario 1 and abatement costs for BEV increase to 1,550 euro

²² See estimates of the German Federal Transport Authority here.

 $^{^{23}}$ It is likely that the vehicle will be used outside of Germany at some point during those 18 years. However, this is not relevant for a calculation regarding global CO_2 emissions and abatement.

²⁴The CO₂ intensity of the power grid is a crucial parameter in this calculation. In contrast to Rapson and Muehlegger (2023), we use average CO_2 intensity instead of marginal CO_2 intensity. Rapson and Muehlegger (2023) argue that "EV load becomes part of the baseline" as the fleet grows, so that average CO_2 intensity might capture BEV emissions better in the long-term. Given that our calculation is based on the full vehicle lifespan of 18 years, average CO_2 intensity is more suitable in our context. In addition, German CO₂ intensity is likely to decrease over the coming decades. In order to put this calculation into context, if Germany reached CO₂ intensity levels of 150 gCO₂/kWh (comparable to the current Danish CO₂ intensity of the power grid), this would amount to 2.15 kgCO₂/100km for a German BEV.

per tonne of CO_2 . Results in Scenarios 3 and 4 for PHEVs are included for completeness, but we do not regard range anxiety as a relevant issue for this market segment.

Two aspects are noteworthy. First, the absolute level of the calculated abatement costs are high if compared to recent estimates of the social cost of carbon (Environmental Protection Agency 2022). However, high initial abatement cost can be justifiable given the goal of spurring consumption at an early stage of technology adoption, which can help unlock learning-by-doing benefits among manufacturers, and adopting an ambitious time frame of largely decarbonizing the transportation sector by mid-century.²⁵ Second, the relative difference in abatement costs between BEVs and PHEVs is substantial and warrants a discussion on whether public subsidy schemes for PHEVs are an efficient policy instrument with respect to abatement costs, at least compared to subsidies to BEVs.

6 Conclusion

This paper analyzes the effectiveness and heterogeneous effects of the consumer purchase subsidy program for electric mobility in Germany, Europe's largest car market and home market of some of the world's premier car manufacturers. We estimate the program's overall impact on the uptake of battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) using granular data on the universe of new vehicle registrations in Germany. For identification, we exploit time specific policy variation and account for confounding time trends and potentially interacting EU-wide policy setting CO_2 standards at the manufacturer fleet level using registrations in neighboring European countries as a control group. We disentangle the effects of the largely concurrent increases in the ambition level of the German subsidy scheme and the European fleet level CO_2 standards by using the trends of a control group and show that our results are robust to changing the composition of the group of control countries. We then conduct a detailed analysis of the policy's heterogeneous effects with respect to income, ideology- proxied by the share of Green Party votes in federal elections- and degree of urbanization- proxied by population density. This helps us to understand both distributional impacts of the subsidy scheme and the main drivers of these distributional effects.

Our results show that the subsidy program increased new BEV and PHEV registrations by about 1,400% and 600%, respectively, compared to the pre-treatment period. However, we find that a large share of BEV and PHEV registrations was infra-marginal, as only about 40% of BEV and 25% of PHEV registrations are subsidy-induced. The remainder was driven by general time trends and EU regulations on fleet-level CO_2 intensity. We further find that effects are strongly heterogeneous and that the purchase subsidy for BEVs was disproportionately taken up by individuals in wealthier counties and with a higher share of Green Party voters. For PHEVs, heterogeneous effects are less pronounced. Interestingly, concern with respect to vehicle range does not seem to be a major driver of BEV/PHEV uptake in our setting. Finally, we calculate an implied abatement cost of about 870 euro per tonne of CO_2 for BEVs and almost 2,470 euro per tonne of CO_2 for PHEVs in a base-

²⁵ Decarbonizing the electricity grid through subsidies to wind and solar power was relatively expensive in 2010, but levelized costs of electricity generation for these two sources have decreased by almost 70% and 90%, respectively, since then (IRENA 2021).

line policy scenario. In alternative scenarios, abated amounts decrease and abatement costs increase dramatically, especially for PHEVs.

Three main policy conclusions emerge from our analysis. First, our results cast doubt on the overall cost-effectiveness of the subsidy program. Second, the program leads to significant transfers to individuals in high-income regions and, therefore, to concerns over general policy acceptance. Third, the implied abatement cost of the program is especially high for PHEVs, suggesting that subsidies for PHEVs should be discontinued. Subsidies to BEVs may be justified despite the high initial abatement cost given the ambitious time frame of transportation sector decarbonization by mid-century and the expected medium-term cost savings once learning effects accumulate and as the power sector continues to decarbonize.

One limitation of the present analysis is that our data do not allow for a separate investigation of the role of charging infrastructure in the adoption of BEVs and PHEVs, respectively. We consider such an analysis— in the German and in other settings— to be a worthwhile avenue for future research. The sample size in this paper does not allow us to disentangle the relative importance of income, green attitudes and population density in driving the uptake in EV subsidies. Future research on the heterogeneous effects of subsidy programs should address this point. Moreover, in future research it would be important to study and quantify learning-by-doing and scale economy effects of purchase subsidies.

A. Appendix

See Tables 7, 8 and 9 and Figs. 8, 9 and 10.

Sources: Federal Ministry for Economic Affairs and Climate Action; Kreditanstalt für Wiederaufbau; German Customs; Transport Ministry, Baden-Württemberg; Senate Administration for Economy, Energy and Companies, Berlin; Ministry for Economy, Industry, Climate Action and Energy of Northrhine-Westphalia; Ministry for Energiewende, Climate Action and Environmental Protection, Schlewsig-Holstein; Websites of listed city administrations, details available upon request.

Measure		Type of funding	Time period
Panel A: Federal level me	easures		
Immediate action program	n for clean air	Expansion of charging infrastruc- ture for electromobility in especially polluted regions, focus is on funding charging infrastructure for vehicle own- ers that do cannot charge at home	11/2017 - 12/2018
Vehicle tax exemption for	r EVs	Tax exemption for electric vehicles first registered between May 18, 2011 and Dec 31, 2025 for up to ten years (or 2030) from the day of registration. When the exemption expires, tax will be reduced by 50% compared to cars with a combustion engine	11/2016 - 2030
Funding program for elec	tric mobility	Partial grant for purchase of EVs for communal or commercial car fleets and setup of charging infrastructure	2015 - current
KfW 440: Charging static buildings	ons for EVs - residential	grant for purchase and setup of non-public charging stations (e.g. a wallbox), grant is 900 euro per charg- ing point	11/2020 - 2021
KfW 293: Climate protec sized companies	tion offensive for mid-	Loan at reduced interest rates for com- panies and freelancers for investment in climate protection measures. Acquisi- tion of electric vehicles only eligible in combination with further climate protection measures, such construction of facilities that provide low-carbon electricity and heat	03/2020 - current
Panel B: State level measures			
Measure	State	Type of funding	Time period
BW-e-Solar-Voucher	Baden-Württemberg	Grant for acquisition of EVs and wallbox up to 1000 euro and 500 euro, respectively, provided a photovoltaic system has been or will be installed	12/2021 - current
WELMO Berlin		Funding program for small and mid-sized companies and freelancers, encompassing consultation and funding of the setup of charging infrastructure up to 200,000 euro as a de minimis aid	2018 - current
Immediate action pro- gram electric mobility	North-Rhine Westphalia	Funding of charging infrastructure for households and companies	2017 - 2018
Climate protection for citizens	Schleswig-Holstein	Funding of purchase, setup and con- necting stationary, non-public charging infrastructure	06/2020 - 2023
Funding program charg- ing infrastructure Panel C: Munici- pal level measures (selected)	Schleswig-Holstein	Funding of expansion of charging infrastructure	07/2020 - 12/2022

Measure		True of funding	Time namiad
Measure	Municipality	Type of funding	Time period
München e-mobil	Munich	Funding of purchase or leasing of EVs up to 25% of acquisition (leasing) costs. Funding of costs for charging infrastructure also possible.	01/2019 - 12/2020
Support for charging infrastructure	Bad Segeberg	Funding of charging infrastructure for households and companies. Grant up to 50% of total costs up to max. 1,000 euro	2015 - 2026
Free parking	Berlin	Free parking during charging	2018 - current
	Hamburg	Free parking in general	2015 - current
	Munich	Free parking (max. 2h)	2018 - current
	Cologne	Free parking in general	2019 - current
	Frankfurt a. M.	Free parking during charging	2019 - current
	Stuttgart	Free parking in general	2012 - 2022
	Düsseldorf	Free parking in general	2019 - 2023
	Leipzig	Free parking (max. 4h)	2016 - current
	Dortmund	Free parking in general	2018 - current
	Essen	Free parking in general	2019 - 2022
	Dresden	Free parking (max. 2h)	2019 - 2022
	Hannover	Free parking (max. 2.5h)	2016 - 2026
	Wuppertal	Free parking during charging	2021 - current
	Bonn	Free parking in general	2016 - 2022
	Karlsruhe	Free parking in general	2015 - 2022
	Wiesbaden	Free parking in general	2019 - 2024
	Mönchengladbach	Free parking in general	2019 - current
	Gelsenkirchen	Free parking in general	2019 - current
	Aachen	Free parking in general	2018 - current
	Chemnitz	Free parking in general	2021 - 2023
	Kiel	Free parking in general	2010 - current
	Braunschweig	Free parking in general	2014 - 2023
	Göttingen	Free parking in general	2017 - 2023
	Celle	Free parking in general	2016 - 2026
	Osnabrück	Free parking in general	2016 - current
	Emden	Free parking (max. 2h)	2021 - 2023
	Nienburg	Free parking in general	2015 - current
	Fürth	Free parking (max. 2h)	2022 - 2024

Table 7 (continued)

Table 7 (continue	d)		
Measure		Type of funding	Time period
	Bayreuth	Free parking in general	2015 - current
	Weiden	Free parking in general	2015 - current
Bus lanes	Dortmund	EVs can use bus lanes	2017 - current
	Essen	EVs can use bus lanes	2017 - current
	Düsseldorf	Separate lane for buses, cabs, bicycles and EVs	2019 - current

Table 8 BEV/PHEV support policies in control pool countries

Sources: European Automobile Manufacturers Association (ACEA) for EU, Cerruti et al. (2024) for Switzerland.

		Subsidy policies		Tax incentives at acquisition		
		2019	2020	2021	2019 2020	2021
Austria	BEV	3,000€			VAT deduction exemptions	and tax
	PHEV	1,500€			-	
Belgium	BEV	-			Minimum regis tax & tax exem	stration ption
	PHEV	-			Tax ex- emption (Flanders)	-
Denmark	BEV	-			Only pay 20% of registra- tion tax and deduction of DKK 40,000 in tax base	Only pay 40% of regis- tration tax and deduc- tion of DKK 170,000 in tax base
	PHEV	-			Only pay 20% of registra- tion tax and deduction of DKK 40,000 in tax base	Only pay 45% of regis- tration tax and deduc- tion of DKK 50,000 in tax base

		Subsidy policies			Tax incentives at acquisition		
		2019	2020	2021	2019	2020	2021
France	BEV	Feebate of up to $6,000 \in \&$ scrappage payment of up to $5,000 \in$	Feebate of u payment of u	p to 7,000€ & scrappage ıp to 5,000€	Region exempt or 50% tion tax	s provid ion (eit) of reg	le an her total jistra-
	PHEV	Feebate of u to 5,000€	p to 6,000€ &	scrappage payment of up	Region exempt or 50% tion tax	s provid ion (eit) of reg	le an her total jistra-
Luxembourg	BEV	5,000€	5,000€	Up to 8,000€	-		50% reduc- tion in regis- tration tax
	PHEV	2,500€	2,500€	1,500€	-		50% reduc- tion in regis- tration tax
Sweden	BEV	SEK60,000	SEK60,000	SEK70,000	-		
	PHEV	SEK10,000	SEK10,000	SEK10,000-SEK59,000	-		
Switzerland	BEV	-		_*	-		

Table 8 (continued)

This overview lists national purchase subsidy schemes and tax incentives at acquisition in the control group countries between 2019 and 2021. *Swiss cantons can introduce subsidy schemes at a local level. To the best of our knowledge, during our relevant period only two cantons (Schaffhausen and Valais) introduced such schemes in 2021.

Table 9 Weights of donorcountries in synthetic controlestimation

PHEV -

Donor country	Weight (EV)	Weight (PHEV)
Austria	0.031	0.113
Belgium	0.726	0.058
Denmark	0.115	0.090
France	0.077	0.573
Luxembourg	0.014	0.058
Sweden	0.018	0.029
Switzerland	0.019	0.077

This table presents the optimal weights resulting from applying the synthetic control method to EV and PHEV registrations in Germany. The donor pool is restricted to the seven Western neighbors of Germany shown in the table.



(a) BEV - Difference observable vs. synthetic

(b) PHEV - Difference observable vs. synthetic

Fig. 8 Synthetic Control results - short pre-treatment period. Note: This figure presents the robustness results of our synthetic control estimation. Panels (a) and (b) present the evolution of registrations per 100.000 inhabitants in Germany and the synthetic counterfactual for BEVs and PHEVs, respectively. The pre-treatment period is restricted to January 2015 to October 2018. The resulting ATTs per 100.000 inhabitants are: Panel a) 8.38, Panel b) 4.38.

Sources: European Alternative Fuels Observatory (EAFO), own calculations



(a) BEV - Austria, Belgium, Denmark, Switzerland

(b) BEV - Austria, Belgium, Switzerland



(c) PHEV - Austria, Belgium, Denmark, France, Switzerland

R P 2015 2016 2017 2018 2019 2020 2021 2022 Month

(d) PHEV - Austria, Belgium, France, Switzerland

Fig. 9 Synthetic control results under different sets of donor pools. Note: This figure presents robustness results of our synthetic control estimation. All panels visualize the difference between treatment and synthetic control under different donor pools. The dotted line represents the first increase of the subsidy in October 2019. The resulting ATTs after October 2019 are: (a) 9,45, (b) 11,28 (c) 4,73 and (d) 9,56



Fig. 10 Robustness tests on main subsidy effect. Note: The figure compares point estimates and 90% confidence intervals of the main subsidy effect on BEV and PHEV uptake ("Reform 2" coefficients) when varying the set of control countries used in the de-trending approach. The first point estimate shows the baseline causal effects for the price segment of vehicles below 65,000 euro as reported in Table 3. The remaining estimates show the same effect when excluding a subset of countries from the set of control countries

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