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Assessing the effectiveness of financial incentives on electric vehicle adoption in Europe: Multi-period difference-in-difference approach

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ABSTRACT

Electric vehicles (EVs) are considered a promising alternative to achieve a cleaner transportation sector. In the last decade, European countries have implemented financial incentive policies to boost EV adoption. This paper estimates the impacts of these policies on EV adoption in Europe using data from 30 countries from 2012 to 2021 and a multi-period difference-in-differences approach. Our results reveal that purchase incentive policies are associated with increased registrations of battery electric vehicles and plug-in hybrid vehicles, and that the effect holds over time. However, the magnitude and duration of these effects are more significant for battery electric vehicles. Ownership incentive policies do not contribute to EV registrations for either type. Further, the results suggest that policy impacts vary between countries with different levels of gross domestic product per capita and renewable energy consumption. These results contribute to the literature on evaluating financial incentive policies for EV adoption, enabling improved decision making by policymakers.

1. Introduction

The transportation sector was responsible for 37 % of carbon dioxide emissions (CO_2) global emissions in the final end-use sectors in 2021 (IEA, 2023a); of these emissions, about three-quarters came from road transport (IEA, 2022), including passenger cars (light-duty vehicles- LDVs) and trucks carrying freight. Electric vehicles (EVs), both battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), are becoming one of the most promising solutions to reduce or entirely negate fossil fuel consumption and mitigate greenhouse gas emissions of the transportation sector (Abo-Khalil et al., 2022; ICCT, 2021) because they operate on low-carbon electric

Abbreviations: ACEA, European Automobile Manufacturers Association; ATT, Average treatment effect for the treated; BEV, Battery electric vehicles; CAD, Canadian dollars; CDF, Cumulative distribution function; CO_2, Carbon dioxide; DID, Difference-in-differences; EAFO, European Alternative Fuels Observatory; EFTA, European Free Trade Association; EREV, Extended-range electric vehicle; EU, European Union; EV, Electric vehicle; FE, Fixed- effect; GDP, Gross domestic product; HEV, Hybrid electric vehicle; ICEV, Internal combustion engine vehicle; IEA, International Energy Agency; LDV, Light-duty Vehicle; PHEV, Plug-in hybrid electric vehicle; POS, Point of sale; PSM, Propensity score matching; R&D, Research and development; TCO, Total cost of ownership; TWFE, Two-way fixed effects; UK, United Kingdom; US, United States; USD, United States dollars; VAT, Value-added tax; ZEV, Zero-emissions vehicle.

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power and have higher energy efficiency compared to internal combustion engine vehicles (ICEVs) (Peng et al., 2017). Using EVs can contribute other environmental benefits, such as improved air quality and reduced noise pollution (Coffman et al., 2017; Kumar and Alok, 2020). Another advantage of EVs is the possibility of using their battery as a resource to deal with fluctuations in electricity demand and to regulate the power grid in real time, contributing to the integration of intermittent renewable energy sources, such as solar energy (Lamedica et al., 2019; Mohammad et al., 2020; Bibak and Tekiner-Moğulkoç, 2021). Despite the benefits, there are still many barriers to EV adoption, vehicle ownership costs, driving range and charging time, supporting charging infrastructure, and high acquisition costs (Coffman et al., 2017).

In the last decade, policymakers have implemented financial and non-financial incentives aiming to increase EV adoption. Financial incentive policies span both the supply and demand side (Melton et al., 2020; Liu et al., 2021). On the supply side, financial incentives in the form of tax exemptions for zero-emission cars, special credits, research and development (R&D) subsidies, and reduction of the income tax have stimulated the widespread adoption of LDVs and supported the scale of EV and battery manufacturing (IEA, 2023b; ACEA, 2021b). On the demand side, financial incentives in the form of direct purchase subsidies, registration tax rebates, and tax exemptions based on exemptions (Yao et al., 2020) have been applied to make the EV price comparable to that of the ICEV. Our study focuses on demand-side financial incentives.

Demand-side financial incentives have been in place in Europe for over a decade. In 2010, 16 European countries provided financial incentives for consumers buying EVs and another seven countries provided their consumers implicit tax incentives (Münzel et al., 2019). By 2022, of the 27 European Union member countries, only Estonia had not yet implemented any financial incentive policies. Financial incentive policies demand high investments from governments (Lu et al., 2022). In Europe, between 2019 and 2021, government investments per electric car was between 5,000 USD and 6,000 USD (IEA, 2021). Financial incentives have also been used in other parts of the world. For instance, in 2020, the United States (US) government made available a federal tax credit of up to 7,500 USD for the purchase of an EV (IEA, 2021), and in 2021, the Canadian government announced a 1.3 billion USD investment to extend the zero-emissions vehicle (ZEV) Incentive Program until March 2025 (Government of Canada, 2023).

Given the importance of EVs to sustainable transport and the costs associated with incentives, a substantial literature has developed examining the effects of financial incentive policies on EV adoption. The results have been conflicting. For example, studies conducted in Europe (Yan, 2018; Münzel et al., 2019), the US (Wee et al., 2018), and globally (Wang et al., 2019a) have shown that policies contribute positively to expanding EV adoption. However, some studies have found inconclusive results on the relationship between these policies and EV adoption (Plötz et al., 2016; Jenn et al., 2018).

Furthermore, there are important research gaps that make it difficult to understand the impact of these policies across countries. First, most studies focus on the US or global effects. For example, in the literature review conducted by Münzel et al. (2019), of the eighteen articles identified, only three investigated the impact of policies in Europe. A similar result was found in the review conducted by Austmann (2021). Thus, considering this context and the extension of financial incentive policies for purchasing EVs in most major European markets (IEA, 2022), we focus on Europe to conduct a more specific analysis of the effects of EV policies. A second limitation of the literature is that studies using fixed effects regressions (Jenn et al., 2018; Wee et al., 2018; Azarafshar and Vermeulen, 2020) are not able to provide a dynamic analysis of the effect of policy implementation over time, but rather an estimate of the average impact of the intervention in a single period. This might result in estimates that hide interesting patterns of EV adoption in different countries. Third, studies conducted in Europe (Yan, 2018; Münzel et al., 2019) and even globally (Chandra, 2022; Xue et al., 2021), suggest that policies contribute positively to expanding the EV market. However, the countries in the samples are heterogenous, as they have different levels of economic development, geographic locations (Zheng et al., 2022) and cultural factors. These differences have not been fully investigated.

Lastly, many studies assessing the impact of financial incentive policies on EV adoption do not differentiate between BEVs and PHEVs (Hardman et al., 2017). However, considering the distinct characteristics of these vehicles in terms of their energy source, driving range, performance, emissions, and environmental impact (Rezvani et al., 2015), the policy implications for each vehicle type may be different as these characteristics can influence consumer perception and choice (Hardman et al., 2017; Wee et al., 2018). Thus, our study conducted separate sample estimates for BEVs and PHEVs to provide insights relevant to each vehicle type.

With the aim of extending the scientific literature and assisting policy makers, our study examines the causal relationship between consumer-oriented financial incentive policies and EV adoption. Specifically, we answer the following research questions: (1) What are the effects of financial incentive policies on the share of BEVs and PHEVs registered? (2) What are the effects of implementing financial incentive policies over time? (3) How does the implementation of these policies affect EV adoption in different countries? To answer these questions, we use data from 30 countries from 2012 to 2021. We apply Difference-in-differences (DID) and an event study strategy that considers the staggered way these policies were implemented across countries over the period evaluated.

This study makes several contributions to the understanding of EV adoption. First, we capture the effects over time of financial incentive policy implementations. Second, we show how financial incentive policies impact different groups of countries, based on distinguishing characteristics, such as income and renewable energy consumption. Third, we examine the impact of policies on the European market, adding new insights into these effects in a region that encompasses both emerging and developed markets. Finally, our work introduces a new perspective to an extensively studied subject: the impact of financial incentives on the adoption of BEVs and PHEVs. We achieve these novel contributions by analyzing the impact using a methodological tool that has not previously been explored in this field. Our approach allows us to consider two fundamental aspects related to the implementation of financial incentive policies. First, examining the possibility of a gradual impact after the implementation of these policies makes it possible to understand not only the immediate or average effect of a policy, but also the changes of the effect over time. Given that financial incentive policies can have dynamic effects, it can take several years for these effects to manifest themselves fully. Second, our approach considers that the implementation of policies does not occur randomly due to the characteristics of each country. The methodology used in this study

recognizes this non-randomness of policy implementation, and therefore deals robustly with this potential bias (Callaway and Sant'Anna, 2021).

The rest of the paper is structured as follows. Section 2 presents the literature review. Section 3 gives a brief history of the financial incentive policies that exist in Europe and that are covered in our work. Section 4 describes data and research methodology. Section 5 presents the main results, baseline results, and heterogeneity analysis. Section 6 provides a discussion of the results and policy implications.

2. Review of relevant literature

2.1. Related studies

This review focuses on extant research relevant to contextualizing the research problem, facilitating an understanding of previous approaches, and highlighting the most current debates.

As a first step, we selected studies that used regression and its variations, mainly fixed-effect (FE) regression, to assess the causal relationship between financial incentive policies and EV adoption. This choice was based on the view that regression models, especially FE , may not be the most suitable for assessing the impact of financial incentive policies on EV adoption if their implementation is staggered over time. Second, we selected studies that used time series data related to EV sales or registrations for at least two years. Studies using time series data make it possible to identify and understand trends or patterns and to model relationships between variables over time, differentiating between immediate effects and cumulative effects of policies over the years. The third set of articles assessed different types of financial incentives in an aggregated or disaggregated manner, because different incentives can have different impacts on the adoption of BEVs and PHEVs. Although many different studies with the aforementioned characteristics were examined, given the significant number of studies on the subject, our intention is not to provide an exhaustive review, but rather a concise discussion that offers the necessary context for the research.

Studies evaluating the effects of financial incentive policies on EV adoption commonly use FE panel data regressions because this method enables the processing of time series data from different countries or regions (Austmann, 2021). For instance, Chandra (2022) collected data from ten countries between 2013 and 2019 and applied two-way fixed effects (TWFE) regression to analyze the impact of policies and incentives, fuel price, and renewable energy in total electricity production on demand for BEVs and PHEVs. The study shows that financial incentives have a positive impact only for BEVs, while on PHEV demand there was no significant impact. In comparison, Wee et al. (2018) assessed how subsidies and other policy instruments affected new BEV and PHEV registrations in 50 US states between 2010 and 2015, finding a positive impact of financial incentives for both BEVs and PHEVs, with the estimated coefficients for BEVs almost twice as large as those for PHEVs. Meanwhile, Azarafshar and Vermeulen's (2020) analysis of BEV and PHEV sales data in Canadian provinces from 2012 to 2016 shows that incentives have a greater impact on BEVs than PHEVs.

To understand the effectiveness of different financial incentives, most studies seek to evaluate them individually or further classify them based on how often they are applied (i.e., recurring or one-time) (Münzel et al., 2019), whether they are obtained at the time of purchase (direct) or after purchase (indirect) (Plötz et al., 2016), and whether they are incentives or disincentives (Hardman, 2019). For instance, Münzel et al. (2019) evaluated the impact of financial incentives on EV sales in 32 European countries between 2010 and 2017. The results indicate that rebates, point of sale (POS) tax benefits, and recurring incentives are positive and significantly correlated with EV market share; however, income tax credits show a negative relationship. Clinton and Steinberg (2019) evaluated the influence of vehicle purchase subsidies on BEV adoption in the US between 2010 and 2014. Their analysis found that rebates have a positive impact on new BEV registrations, but the same was not observed for tax credits. Münzel et al. (2019) and Clinton and Steinberg (2019) explain that the limited temporal variability of the tax credit data in their samples (i.e., time of exposure to this incentive) could explain the lack of a statistically significant effect or a negative effect of this incentive on EV adoption. In the same vein, Wang et al. (2017) analyzed data from Chinese cities between 2013 and 2014 and concluded that tax credits were not a significant factor in EV sales in this context. On the other hand, Li et al. (2017a) investigated the impact of the tax credits in the US, using EV sales data between 2011 and 2013 and found that tax credits of up to 7,500 USD had a significant positive effect. Xue et al. (2021) evaluated the relationship between purchase subsidies, registration tax benefits, ownership tax benefits, and EV market expansion in 20 countries between 2015 and 2019, from which they concluded that ownership tax benefits are one of the key factors for this expansion.

Assessing financial incentives in aggregate, Shang et al. (2024) also concluded that purchase subsidies can increase the sales and market share of EVs, using data from Chinese cities between 2016 and 2019. Using US data from 2010 to 2015, Jenn et al. (2018) found similar results. In contrast, Liu et al. (2021) identified that purchase subsidies for EVs in Chinese cities between 2009 and 2018 were ineffective in promoting these vehicles. We note that the results to date are conflicting and ambiguous. This may be because studies do not consider the effect of these incentives over time or that the different countries/states represent a heterogeneous sample, hence the need for further research.[1]

In our review of the literature, we found one study that considers the impact of incentives over time and performs a heterogeneity analysis. In that study, Zheng et al. (2022) evaluate the impact of financial incentive policies on EV sales, considering data from 286 Chinese cities from 2009 to 2018. To do so, they used the DID and propensity score matching (PSM) approaches. The results considered the dynamic effects of the policies and show that a policy becomes effective immediately after its implementation, with increasing

[1] For more information on studies that have used regression models to assess the impact of financial incentives on EV adoption, see Münzel et al. (2019) and Austmann (2021).

positive effects in the following years. The authors further evaluated the effect of the policies by EV type and across cities and regions. They find that policies have a more significant effect on BEVs than PHEVs. They conclude that the most significant impact of the financial incentive policy occurs in the larger cities, due government's ability to implement financial incentive policies in urban centers, and in the central region of China. Table 1 provides a summary of the relevant studies, including an overview of the data sets, the regression methods, types of incentives used, and the relationship of these incentives on EV market penetration.

Informed by this work, we design our research to analyze the causal relationship between policies incentives and EV adoption through estimates of the dynamic effect of policies and heterogeneity analysis in a broader context than in a single country. To understand the effects of policies incentives, we must first consider the conditions and factors within the country that may also influence adoption. Therefore, our model includes the control variables related to percentage of renewable energy consumption, gasoline price per liter, and gross domestic product (GDP) per capita to better isolate the specific effects associated with policies. The following sections present a discussion of each control variable used in this study.

2.2. Renewable energy

The penetration of renewable sources and EVs are considered essential to reduce the problems related to CO_2 emissions (Bibak and Tekiner-Moğulkoç, 2021). Studies have used two main ways to measure the influence of renewable energy — as part of electricity production and as consumption — and they have found statistically significant results. For example, Li et al. (2017b) investigated the impact of renewables as part of the total electricity production and other socio-economic variables on EV demand using data from 14 global countries between 2010 and 2015. They conclude that a one percent increase in renewables can provide a 2–6 % growth in EV demand. This result is similar to those found by Neves et al. (2019) and Chandra (2022). This effect may occur because of the environmental consciousness of consumers who feel more motivated to purchase an EV when the batteries are recharged using renewable energy sources (Chandra, 2022). Ruoso and Ribeiro (2022) also found a positive correlation between EV adoption and percentage of renewable energy consumption using data from 28 global countries between 2010 and 2020.

2.3. Fuel price

EVs generally have a higher purchase price compared to ICEVs, but the long-term operating cost can be much lower because electricity is subject to a lower level of taxation compared to fossil fuels (Palmer et al., 2018). Lévay et al. (2017) evaluated the total cost of ownership (TCO) of BEVs and PHEVs through a comparison with their ICEV peers using data from eight European countries in 2014. They concluded that the average electricity expenses of BEVs represent between 31 % and 52 % of the average fuel expenses of ICEV, while for PHEVs these expenses represented between 65 % and 81 %. Thus, in a scenario where fossil fuel prices are high, ICEV owners may feel financial pressure and consider energy-efficient vehicle options, such as EVs (Chandra, 2022). Along this line of reasoning, some studies have observed that fuel prices are a significant predictor of EV adoption. For example, Wang et al. (2019a) evaluated data from 30 global countries in 2015 and conclude that fuel price has a positive and significant relationship with EV market share. This result is consistent with those reported in the studies by Li et al. (2017b), Wee et al. (2018) and Zheng et al. (2022). However, other studies have found that fuel price is not a significant predictor or has a negative relationship on EV market share (Jenn et al., 2013; Sierzchula et al, 2014; Azarafshar and Vermeulen, 2020).

2.4. Gross domestic product

Some studies have found a positive and significant relationship between GDP and EV adoption (Harrison and Thiel, 2017; Chandra, 2022; Alali et al., 2022). Research suggests the penetration rate of EVs is higher in countries with a higher GDP per capita because consumers in these countries can pay a premium for EVs (Ajanovic and Hass, 2016). New technologies also tend to diffuse more quickly in countries with a higher GDP (Ruoso and Ribeiro, 2022). High-GDP countries are able to invest more in charging infrastructure (ACEA, 2021c) and provide financial incentives to encourage EV adoption (Alali et al., 2022). In Europe, countries with an average GDP per capita lower than 17,000 euros have an EV market share lower than 3 %, while in countries with an average GDP per capita higher than 46,000 euros, the EV market share exceeds 15 % (ACEA, 2021c).

3. Financial incentives for electric vehicles in Europe

Europe has a diversity of financial incentive options for EVs on the demand and supply side, including rebates, home charger subsidies, POS tax reduction, value-added tax (VAT) reduction, income tax reduction, special depreciation, circulation tax reduction, company car tax reduction, electricity supply subsidies, and waivers on fees (Münzel et al. (2019). For more information on these incentives, see studies by Münzel et al. (2019) and Yan (2018). For the demand side, and specifically for passenger EVs in the European Union (EU-27), the incentives are commonly classified in three categories: (1) tax benefits on acquisition, (2) tax benefits on ownership and (3) purchase incentives. Our study focuses on tax benefits ownership and purchase incentives because the former aids in the reduction of operating costs and the latter reduces EV purchase costs.

Incentives grouped under tax benefits on ownership include exemptions or reductions in annual circulation tax, fuel tax, road user fees, and congestion charges (Dineen et al., 2018). We focus on circulation and fuel taxes, which are the most common taxes in Europe. These two taxes complement each other, as in many countries CO_2 emissions per kilometer are one of the criteria for establishing exemptions or reductions in the circulation tax (ACEA, 2021a; ACEA, 2021b). Various studies consider these two taxes as a single tax

Table 1
Overview of relevant studies on the effect of incentives on EV market penetration.

Author (year)	Observations	Time resolution	Vehicle type	Method	Aggregated financial incentives	Disaggregated financial incentives: Rebates, POS tax benefits, registration tax benefits	Disaggregated financial incentives: Tax credit	Recurring incentives (ownership tax benefits, operating incentives)
Plötz et al. (2016)	Europe, US	2010–2014, yearly	EV (BEV/PHEV)	Pooled ordinary least squares (OLS) regression	N	EV*	N	EV*
Wang et al. (2017)	China	2013–2014, yearly	EV (BEV/PHEV)	Stepwise linear regression	N	0	0	0
Li et al. (2017a)	US	2011–2013, yearly	EV (BEV/PHEV)	OLS and Generalized Method of Moments (GMM)	N	N	EV*	N
Jenn et al. (2018)	US	2010–2015, monthly	EV (BEV/PHEV)	FE panel data regression/LDV with GMM estimator	N	EV*	EV*	N
Wee et al. (2018)	US	2010–2015, yearly	EV (BEV/PHEV)	Multi-level FE regression	EV*	N	N	N
Münzel et al. (2019)	Europe	2010–2017, yearly	EV (BEV/PHEV)	FE regression	EV*	EV*	0	EV*
Clinton and Steinberg (2019)	US	2011–2015, quarterly	BEV	FE regression	BEV*	EV*	0	N
Azarafshar and Vermeulen (2020)	Canada	2012–2016, monthly	EV (BEV/PHEV)	Generalised Linear Model (GLM)	EV*	N	N	N
Liu et al. (2021)	China	2009–2018, yearly	EV (BEV/PHEV)	DID and propensity score matching (PSM)	N	0	N	N
Xue et al. (2021)	Global	2015–2019, yearly	EV (BEV/PHEV)	Random effects regression	N	0	N	EV*
Chandra (2022)	Global	2013–2019, yearly	EV (BEV/PHEV)	Two-way fixed effects (FE)	BEV*	N	N	N
Zheng et al. (2022)	China	2009–2018, yearly	EV (BEV/PHEV)	DID and propensity score matching (PSM)	EV*	N	N	N
Shang et al. (2024)	China	2016–2019 (monthly)	EV (BEV/PHEV)	FE regression	N	EV*	N	N

Notes: BEV*: the incentive has a positive and significant effect on the BEV market; EV*: the incentive has a positive and significant effect on the EVmarket; 0: non-significant relationship; N: incentive not evaluated in study.

termed circulation tax or vehicle tax (Yan, 2018; Hauff et al., 2018; Hardman, 2019). Circulation tax can be charged on vehicles registered to circulate on public roads and is usually paid at fixed intervals, usually annually; hence, it is a recurring incentive provided during the lifetime of an EV (Hardman, 2019). For its calculation, besides CO_2 emissions, criteria such as weight, age, class, engine power, engine size, and cylinder capacity of the vehicle may be used (Münzel et al., 2019; ACEA, 2021a). BEVs, PHEVs, extended-range electric vehicles (EREVs), and hybrid electric vehicles (HEVs) usually benefit more from this tax, because their emissions are lower than those of the ICEVs. Depending on the tax structures in place, these vehicles may be exempt from the tax or have a substantial reduction. PHEVs tend to benefit the least from this incentive as policy makers try to encourage vehicle owners to choose more fuel-efficient and environmentally friendly vehicle models.

Purchase incentives include subsidies provided for the purchase of EVs, and they are usually applied on a one-time basis. They can be financial discounts, tax credits, or rebates (Hardman, 2019) and are easier for consumers to understand (Münzel et al., 2019) because they are often provided as direct discounts with fixed values easily disclosed by manufacturers and sellers (Select Car Leasing, 2021). This structure also makes it possible to compare these incentives more easily between countries (Yan, 2018). For example, in 2021, Slovenia and Ireland offered incentives of7,500 euros and 5,000 euros to buyers of BEVs. In general, purchase incentives are determined based on criteria such as the class (passenger car, vehicle for carriage of passengers, vehicle for carriage of goods), the price, the type of the vehicle (BEVs, PHEVs, HEVs and EREVs), buyer's income, and CO_2 emissions per kilometer. The implementation of these incentives may be restricted to a few cities in a given country, be linked to a specific period, and depend on limited funds.

Fig. 1 shows the countries that offered purchase and ownership incentives between 2012 and 2021. We consider 2012 as our baseline because that was when BEV sales started to gain momentum (Hardman et al., 2017). Most countries have continually maintained financial incentives throughout the ten years. Generally, the incentives were provided for BEVs and PHEVs, meaning no government implemented incentives covering only one vehicle type. By 2022, 17 European countries had adopted some purchase incentives, and 21 had adopted ownership incentives. Some countries, such as France and Belgium removed financial incentives, and countries like Portugal and Luxembourg also removed them, but then reintroduced them a few years later. On this point, Vilchez et al. (2019) find that significant reductions or removal of purchase subsidies and circulation tax exemptions can affect the market share of EVs in Europe.

4. Data and methodology

This study includes data from 30 European countries: Austria, Belgium, Bulgaria Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom. The period of study is from 2012 to 2021 for two reasons. First, Europe has strict fuel economy and emission regulations that encourage EV use. In addition, 12 European countries adopted targets for zero-emission vehicles (ZEVs). The second reason relates to data availability. Although a dataset is available from the European Alternative Fuels Observatory (EAFO), the European Commission's leading reference portal for alternative fuels, infrastructure and vehicles in Europe, not all countries have publicly available data or consistently collect data. For this reason, the sample was limited to thirty countries with characteristics relevant to this study and having open data availability.

4.1. Data description

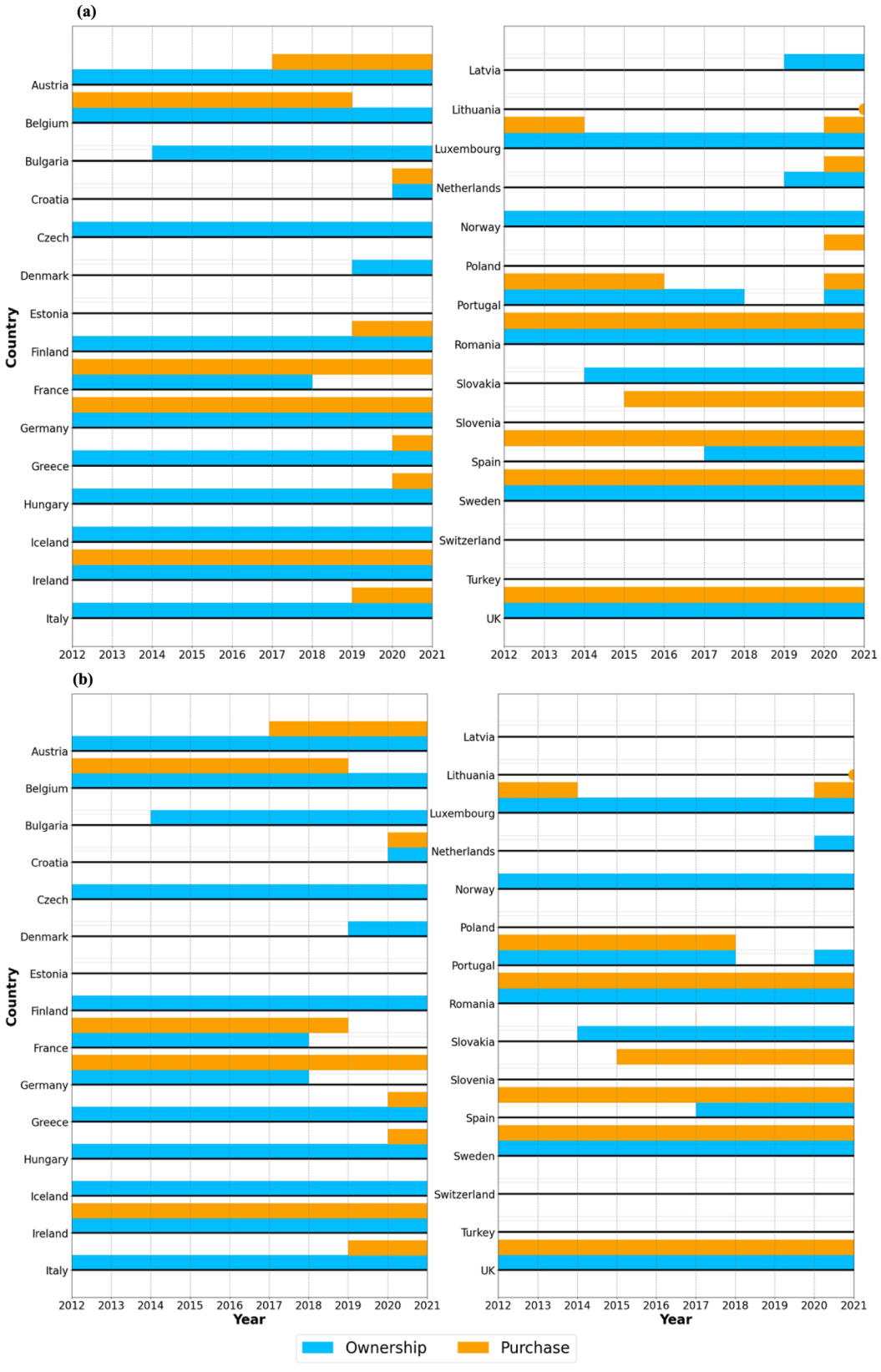
4.1.1. Dependent variables

Two dependent variables are examined: new registrations of BEVs (1) and of PHEVs (2) as a percentage of the total number of registrations. Registration shares are chosen instead of sales shares because the eligibility of financial incentive policies is based on registrations, not sales (Clinton and Steinberg, 2019; Münzel et al., 2019). In addition, sales share can include vehicles sold outside the country or vehicles purchased but not on the road (Fuinhas et al., 2021). Furthermore, EV registration as a percentage of the total number of registrations make it possible to eliminate the effect of variations in the size of the vehicle market. Because our research focuses on consumer adoption of EVs, only LDVs are included.

Fig. 2 shows the percentages of newly registered BEVs and PHEVs by country between 2012 and 2021. The countries with the largest BEV markets in 2021 were Norway (64.45 %), Iceland (33.45 %), Netherlands (19.95 %) and Sweden (19.09 %). With the exception of the Netherlands, these countries also have the largest markets for PHEVs, but in this category, the largest penetration is in Iceland (38.27 %), followed by Sweden (25.86 %) and Norway (21.65 %). More than half of the countries have a market share for both BEVs and PHEVs below 5 %.

4.1.2. Independent variables

The independent variables are: (1) tax benefits for ownership, including exemption or reduction in circulation tax and fuel tax, and (2) purchase incentives, including income tax credits or rebates. Consistent with the literature, we consider purchase incentives to be provided one time and ownership incentives to be recurring. We classified incentive policies following the classification adopted by European Automobile Manufacturers Association (ACEA) and previous studies such as Yan (2018) and Xue et al. (2021). Policies applied at the national, regional and city level for light-duty passenger vehicles were considered. These variables are represented in 0/1 indicators (binaries), for countries and years when incentives policies were in place (Chandra, 2022; Liu et al., 2022; Zheng et al., 2022).



(caption on next page)

Fig. 1. Summary of customer-oriented financial incentives in Europe between 2012–2021 for (a) BEVs and (b) PHEVs. .
Source: Author, summarized from European Automobile Manufacturers Association's (ACEA) tax guide (2012a, 2012b, 2013a, 2013b, 2014a, 2014b, 2015a, 2015b,2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2021a, 2021b)

4.1.3. Control variables

The control variables are: (1) renewable energy consumption as a percentage of total energy consumption, (2) gasoline price, and (3) GDP per capita. Gasoline price is expressed in USD and is the monthly average prices per liter of unleaded gasoline, including taxes and fees. GDP per capita is also in USD and has been divided by 1,000 to present the values on a smaller scale. All monetary values were adjusted to the base year of 2021. Table 2 presents the descriptive statistics of the variables for the 30 countries between the years 2012 and 2021.

4.2. Data collection

The annual data for the percentage of newly registered BEVs and PHEVs were collected from the EAFO and International Energy Agency (IEA). For countries with some missing data, we used a linear interpolation method to complete them.

The presence and magnitude of financial incentives for BEVs and PHEVs were identified through the Tax Guides and Overview on tax incentives for electric vehicles in Europe of ACEA. However, when the magnitudes for purchase incentives were not available in these data sources, we turned to the studies by Yang et al. (2016) and Münzel et al. (2019). A detailed assessment of the scope of these incentives was carried out as follows. First, we identified whether the incentives were intended for BEVs or PHEVs. When this information was not explicit, we used the amount of CO_2 emissions to make a determination. For example, in some countries, tax benefits for vehicle purchases were applied to vehicles that emitted less than 50 g CO_2/km (tank to wheels) in 2021. In this case, the policies were considered to apply to both, because BEVs emit on average 0 g CO_2/km and some categories of PHEVs emit less than 50 g CO_2/km (Thiel et al., 2010; Fritz et al., 2019). Second, we checked whether incentive policies were applied at the national, regional and city level. Finally, we checked whether the policies applied to passenger vehicles, excluding those targeting vehicles transporting passengers or goods.

Renewable energy data were collected from the BP Statistical Review of World Energy. GDP per capita data were obtained from the World Bank Open Database. The gasoline price data was collected from different sources, including: (1) UK government website, (2) Trends Economics website, (3) Organization for Economic Cooperation and Development (OECD), and (4) ACEA's Tax Guides. We converted these data to USD and adjusted for inflation (base year 2021) using the consumer price index (2010 = 100) data from the World Bank Open Database and Exchange rate- GBP to USD data from the Statista website. Table 3 summarizes the data sources used to create our database; all are open data sources except Statista which requires a subscription.

4.3. Empirical model

4.3.1. Differences-in-differences

Differences-in-differences (DID) is a statistical method used in empirical studies to assess the causal impact of an intervention or policy on a population (Callaway and Sant'Anna, 2021; Zheng et al., 2022). The method compares the average change in a dependent variable, in our case, the registration share of BEVs and PHEVs, over time in two different groups: one group receiving the intervention (treatment group) and another group not receiving it (control group). In our case, the intervention or treatment is exposure to the financial incentive policy. Thus, when a group of countries was exposed to policy, we say that this group was treated. The general formula for DID, similar notation used in Yu et al., (2021) and Roth et al. (2023), is defined by:

$$Y_i = D_i Y_i(1) + (1 - D_i) Y_i(0) \tag{1}$$

Where $D = 1$ for countries (i) that received the policy and $D = 0$ for countries in the control group. One of the main measures of treatment effect used in DID is the average treatment effect on the treated (ATT) (Callaway and Sant'Anna, 2021; Caetano et al., 2022), which is the average difference in the registration share of EVs over time between the control group and the treatment group. The ATT is calculated as:

$$\text{ATT} = \text{E}[Y_{it}(1) - Y_{it}(0) | D_i = 1] \tag{2}$$

Where Y_{it} represents the average change of the registration share of country i in year t. DID assumes the validity of the hypothesis that the average results for treated and control groups would have followed parallel trajectories over time, known as the parallel trend hypothesis (Kreif et al., 2016).

4.3.2. Two-way fixed effects

The conventional implementation of interventions in DID settings uses two-way fixed effects (TWFE) linear regression specifications (Angrist and Pischke, 2009; Yu et al., (2021). This model controls for time invariant unobserved characteristics and time common effects, respectively. Based on the study parameters the model specification is defined by the equation:

$$\log(\mathit{EVregistration} + 0.0001)_{it} = \beta_0 + \beta \mathit{policy}_{it} + \mu_i + \mu_t + \log(\phi X_{it} + 0.0001) + \epsilon_{it} \tag{3}$$

Where *EVregistration* represents natural logarithm of newly registered EVs (BEVs or PHEVs) in country i in year $t = 2012, \ldots, 2021$.

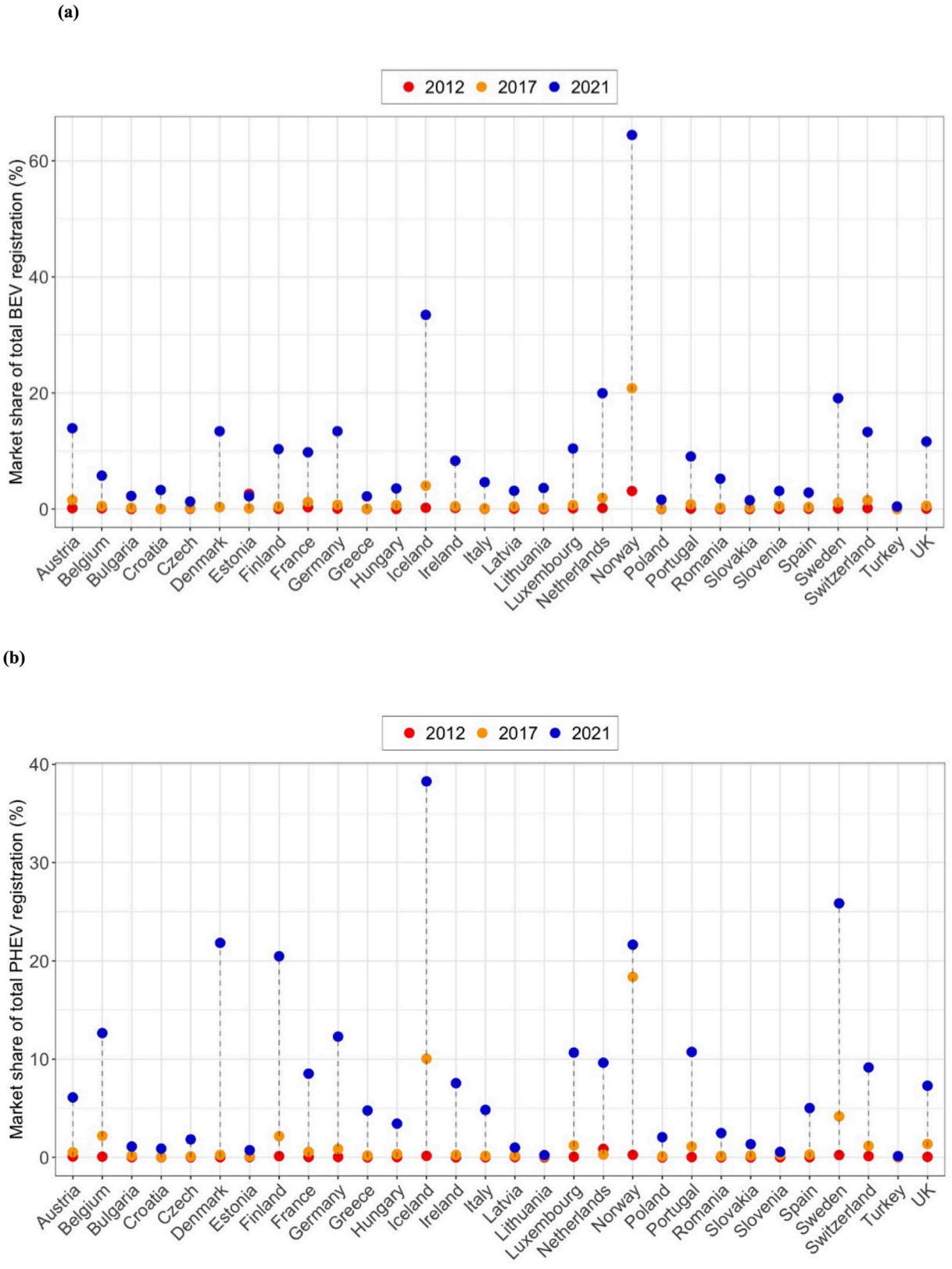


Fig. 2. Market share of total registration (%) (a) BEVs and (b) PHEVs by country in the years 2012, 2017, and 2021. Data). Source: The data are from European Alternative Fuels Observatory (EAFO, 2022)

Table 2
Descriptive statistics.

S.no	Variables	Variable definition	Obs.	Mean	S.D.	Min.	Max.
1	Percentage BEV	Newly registered BEVs (%)	300	2.676	6.959	0	64.45
2	Percentage PHEV	Newly registered PHEVs (%)	300	2.169	4.920	0	38.27
3	Ownership_EV	1 if ownership policy is available to EV buyers, 0 if not	300	0.660	0.474	0	1
4	Purchase_EV	1 if purchase policy is available to EV buyers, 0 if not	300	0.407	0.492	0	1
5	Magnitude purchase BEV	Value of the purchase incentive for BEV (in USD)	300	1897.188	2914.550	0	10000.0
6	Magnitude purchase PHEV	Value of the purchase incentive for PHEV (in USD)	300	1067.425	1964.506	0	7164.036
7	Gasoline price	The average annual gasoline price (USD/l)	300	1.708	0.357	0.897	2.743
8	GDP	GDP per capita (in USD)	300	41.228	27.783	7.975	135.376
9	Renewable consumption	Renewable energy share in total energy consumption (%)	300	0.211	0.178	0.0299	0.872

Table 3
Variables and their sources.

Variables	Country (if the source was exclusive to this country)	Source
Percentage BEV & PHEV		EAFO (2022)
Ownership_EV, Purchase_EV (binary)		ACEA (2012a, 2013a, 2013b, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2021a, 2021b), 2012a, 2012b.
Magnitude_purchase incentive (BEV, PHEV)		ACEA (2012a, 2013a, 2013b, 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2017a, 2017b, 2018a, 2018b, 2019a, 2019b, 2020a, 2020b, 2021a, 2021b), 2012a, 2012b, Yang et al. (2016), Münzel et al. (2019).
		UK Government (2013)
	Croatia (2012)	Trading Economics (2022)
Gasoline price	Iceland	ACEA (2012a, 2013a, 2014a, 2015a, 2016a, 2017a, 2018a, 2019a, 2020a, 2021a)
	Norway, Turkey, Switzerland	OCDE (2022)
Exchange rate- GBP to dollar USD		Statista (2023)
Consumer price index (2010 = 100)		World Bank Open Database (2022a)
GDP		World Bank Open Database (2022b)
Renewable consumption		BP Statistical Review of World Energy (2022)

β_0 represents the model constant. *policy* is the binary variable indicating the ownership incentive policy of EVs, which is equal to 1 if country i implemented it in year t and 0 otherwise. The coefficient β is the DID estimator and represents the difference in market share registration EVs between the countries that received the policy intervention and those that did not. In the case of the incentive purchase policy, *policy* is a continuous variable representing the magnitude of this policy implemented by country i in year t. The coefficient β is the DID estimator and reflects the incentive policy's incremental impact on EV registrations' market share. μ_t and μ_i are the fixed effects for the year and country, respectively. X_{it} is the vector of control variables represented by natural logarithm for GDP per capita, renewable energy consumption and gasoline price. ϵ_{it} is the residual error term. The dependent variable and control variables had the value 0.0001 added due to the presence of null values in the database.

4.3.3. Event study

The event study method is an extension of TWFE and allows one to measure the dynamic effect of a policy intervention with a staggered (non-constant) implementation (Borusyak et al., 2021). It includes lead and lag variables (in the form of dummy variables) as regressors, enabling the capture of treatment effects for each time period. The following event study specification can be estimated from the following equation:

$$\log(EVsregistration + 0.0001)_{it} = \beta_0 + \left(\sum_{e=-6, e\neq -1}^{0} \zeta_e D_{it}^e\right) + \left(\sum_{e=1}^{7} \lambda_l D_{it}^e\right)\mu_i + \mu_t + \log(\phi X_{it} + 0.0001) + \epsilon_{it} \quad (4)$$

Where $D_{it}^e = 1$ if country i has been exposed to the policy for e periods in year t, and $D_{it}^e = 0$ otherwise. The leads ζ_e are treatment terms associated with the years before the policy's implementation, allowing us to test the parallel trends hypothesis. The parallel trends indicate that, in the absence of the policy, the trends in the dependent variable (EV registration share) are constant over time for treated and non-treated countries. The dummy for the year prior ($e = -1$) to the treatment is suppressed to avoid the perfect collinearity problem. The term lags λ_e allows for the verification of post-treatment effects and captures the changes in the market share of EVs in treated countries after adopting the policy (where $e = 1$ represents the first year of treatment).

4.3.4. Difference-in-differences with multiple periods

Recent studies have shown that TWFE regression, even when associated with the event study, can produce misleading estimates if the policy was implemented in a staggered way over time and has a heterogeneous effect across units (Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Sun and Abraham, 2021). As the policies were implemented in Europe at different times, we cannot discard the

hypothesis that the dynamics of the effect of these policies depend on the time a country is exposed to them. This means that the dynamic effect may occur if the impact on EV adoption occurs gradually in the years following the implementation of the financial incentive policy. Neither can we discard the heterogeneity hypothesis because the treatment was not randomized across countries. Therefore, there is a possibility that the financial incentive policies adopted in Europe have different impacts between groups of countries. In this context, Callaway and Sant'Anna (2021) developed a more flexible way to estimate the ATT as a function of treatment group g, in which a group is formed according to the period in which the units received the intervention for the first time – in the case of our study, the moment in which the country adopted the policy – as well as according to the different periods t. Thus, we applied the DID with multiple periods proposed by Callaway and Sant'Anna (2021) to estimate the ATT of financial incentive policies on the adoption of EVs. In the following, we present the main steps of the estimation. See Callaway and Sant'Anna (2021) for more information about the method.

The method estimates the average treatment effect for groups of countries that were first treated in period g, for a time t defined by:

$$\mathrm{ATT}(\mathrm{g},\mathrm{t}) = \mathrm{E}[Y_t(1) - Y_t(0)\,|G_g = 1] \tag{5}$$

where $Y_i(g)$ is the potential Y_i outcome (EV registration share) at time t if treated, $Y_i(0)$ is the potential outcome at time t if not treated, and G_g is a binary variable indicating whether the country belongs to the group treated for the first time in period g.

The $\mathrm{ATT}(g,t)$ for group g in period t^3g is given by:

$$ATT(g,t) = E\left[w_g^G\left(Y_t - Y_{g-1}\right)|G_g = 1\right] - E[w_g^C(Y_t - Y_{g-1})|C = 1] \tag{6}$$

$$w_g^G = \frac{G_g}{E[G_g]} \tag{7}$$

$$w_g^C = \frac{\frac{P_g(X)C}{1-P_g(X)}}{E\left[\frac{P_g(X)C}{1-P_g(X)}\right]} \tag{8}$$

where $P_g(X)$ is a generalized treatment propensity score for the group of countries g, given the control variables X, and C is a dummy indicating whether a country has never been treated.

Callaway and Sant'Anna (2021) suggest aggregating $ATT(g,t)$ across groups and over time in several possible ways. In this study, we are interested in aggregating the average effect of policy implementation (treatment) for countries exposed to the policy for exactly e periods (dynamic effect). However, since the event study does not seem to be a suitable option for investigating dynamic effects when heterogeneity of treatment effects concerning the duration of exposure to the treatment is assumed (Sun and Abraham, 2021), we chose to use the parameter proposed by Callaway and Sant'Anna (2021) presented by the equation below:

$$\theta_{es}(e) = \sum_{\forall g} 1(g+e \le T)\mathrm{P}(G = g|G+e \le T)\,\mathrm{ATT}(g,g+e) \tag{9}$$

where (e) is the treatment exposure time and is obtained using the $\mathrm{ATT}(g,t)$ of all groups of countries that were exposed to the policy for e time periods. Then, we can calculate the summary measure of the dynamic effect, aggregating all average treatment effects by exposure time, $\theta_{es}(e)$, according to the following expression:

$$\theta_{es}^0 = \frac{1}{T-1}\sum_{e=0}^{T-2}\theta_{es}(e) \tag{10}$$

Table 4
Dynamic marginal treatment effect of financial incentives policies on BEV registration.

Even time	Ownership		Purchase	
	ATT	Overall ATT	ATT	Overall ATT
Year −6	1.3045 (1.4384)	0.3122 (1.0229)	1.3329 (0.7704)	1.1347** (0.2318)
Year −5	2.6029 (2.5439)		−1.5519 (0.8595)	
Year −4	−2.9090 (1.9533)		0.3636 (0.6365)	
Year −3	2.1491 (3.5134)		−0.4469 (0.8705)	
Year −2	−2.9471 (3.4769)		−0.1112 (0.3539)	
Year −1	−0.1088 (0.5814)		−0.2695 (0.3823)	
Year 0	0.5705 (0.4465)		0.3998 (0.2740)	
Year 1	0.0078 (0.7198)		1.3720** (0.2086)	
Year 2	0.8938 (1.0203)		1.9136** (0.3648)	
Year 3	0.8556 (0.8239)		1.1567** (0.2877)	
Year 4	0.2584 (1.0024)		0.8312** (0.3301)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses.

5. Results and discussion

5.1. Dynamic marginal treatment effects of policies

In this section, we seek to answer the first and second research questions of our study, which aim to understand the effects of financial incentive policies on the share of registered BEVs and PHEVs and the effects of the implementation of these policies over time. For this, we present and discuss the main results of our estimates obtained through the methodology presented in section 4.3.4.

5.1.1. BEV registrations

Table 4 presents the results of the dynamic effect of ATT(g,t); it gives the average year-by-year treatment effect of ownership and purchase incentive policies on the registration of BEVs from 2012 to 2021. For this, we use the parameter presented in equation (9). The results suggest that purchase incentive policies are effective after one year for four years (p-values < 0.05), with the most significant contributions coming in the first two years and the effect diminishing in the following years. In the first year that a country adopted the purchase incentive policies, the share of BEV registrations is estimated to have increased by 137.2 %, 191.4 % in the second year, 115.7 % in the third year, and 83.1 % in the fourth year. The overall ATT of 1.1347, obtained from equation (10), indicates an increase of 113.5 % in the market share of BEV registrations for countries that applied this policy (treatment group) relative to countries that did not (control group) over the entire study period. The estimates suggest that purchase incentive policies are an important determinant of BEV adoption over time. The higher positive impact of purchase incentives in the first two years after their implementation may reflect the initial enthusiasm of early adopters who act quickly to take advantage of the newly introduced benefits (Mukherjee and Ryan, 2020). Furthermore, in most countries, the magnitudes of these policies were not adjusted for some years or were reduced (ACEA, 2019a; ACEA, 2020a, ACEA, 2022a), which can reduce consumers' propensity to buy BEVs (Wang et al., 2019b; Lu et al., 2022).

Our estimate diverges from the trend that Zheng et al. (2022) observed regarding the dynamic effect between EV subsidy policies and EV sales in China. In that study, the authors found that the positive impact of the policies increased over the years, potentially leading to a 621.7 % increase in BEV sales four years after their implementation. Similarly, Clinton and Steinberg (2019) found that the effect of financial incentives on BEV registrations in the US was positive and continued to increase during the evaluation period. On the other hand, Fournel (2023) studied rebate programs in Canada for the purchase of EVs and found that they positively impacted initial BEV registrations. However, this impact diminished in the third year. Haan et al. (2023) in Germany observed an increase in BEV registrations after introducing a subsidy program, although they identified intermittent periods of reduced impact on registrations over time. Our estimates, which suggest the effect of purchase incentives is reduced over time, are more in line with these last two results.

The results for ownership incentive policies show no significant effect on the adoption of BEVs. One reason for this result may be that their value is not high enough to encourage the purchase of BEVs. According to Münzel at al. (2019), the benefits of reduced circulation tax have an average rate of 234 euros/year. Another possible reason could be buyers' lack of knowledge or understanding about the operationalization of this policy (Wee et al., 2018; Vilchez et al., 2019). Furthermore, according to Xue et al. (2021), tax reductions can take three to five years before their tangible benefits become evident.

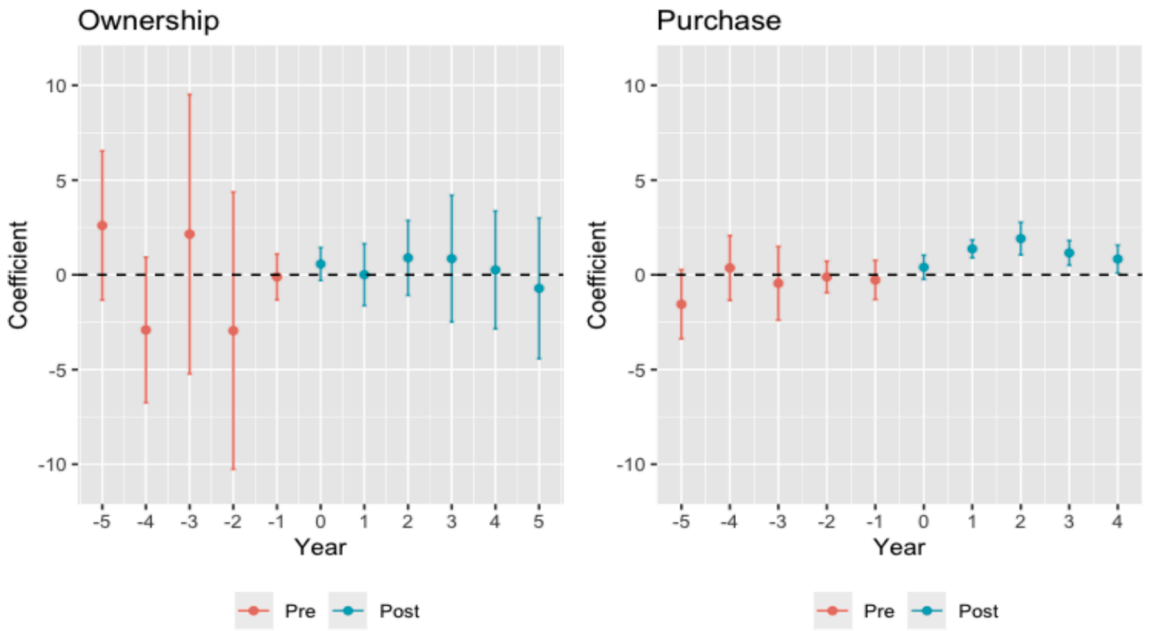


Fig. 3. Dynamic impact of Ownership and Purchase financial incentives policies on BEV registrations.

Fig. 3 shows the dynamic effects of the treatment of ownership and purchase incentive policies on BEV registration. On the *x*-axis, suffixes indicate the base year in which the policy was implemented ($x = 0$), as well as the years before (pre) and after (post) this event. The vertical lines represent the regression coefficients and the 95 % confidence intervals. This analysis shows that the confidence intervals of the pre-event coefficients fluctuate around zero, suggesting that the parallel trend hypothesis is valid (Zheng et al., 2022; He et al., 2023); i.e. the comparison of the time evolution of market share BEV registration for the countries that implemented the financial incentive policies and those that did not in the pre-event period is constant over time, so if there is a variation in the post-event period, it can be attributed to the effect of the policy implementation.

5.1.2. PHEV registrations

The results of the dynamic effect of ATT(g, t) for ownership and purchase incentive policies on the registration of PHEVs from 2012 to 2021 are shown in Table 5. Purchase incentive policies become effective two years after implementation (p-values < 0.05), with the share of PHEV registrations in the second year estimated to have increased by 81.3 %, 88.2 % in the third year and decreased by 112.6 % in the fourth year. This trend could be explained if the policy attracted many PHEV buyers in the initial years, so the demand for these types of vehicles was exhausted after this period. The overall ATT result was insignificant. This result might suggest that the purchase incentive policy had a transitory effect, as it had a strong initial effect, but reduced over time. Moreover, variations in the impact of the policy between treated groups or at specific times after its implementation may have influenced this result.

Comparing our results to previous work, Zheng et al. (2022), which evaluated the impact of subsidies on the adoption of PHEVs over time, found that this impact gradually increased four years after the policy implementation. However, like our findings, the policy only began to have an effect in the second year after its implementation, and over time, its effect proved to be more pronounced for BEVs than for PHEVs. Similar to our findings, the results of Haan et al. (2023) show a positive impact of rebates on the promotion of PHEVs over the years but with fluctuations in the effect, leading to periodic variations of increase and decrease. The results of Sheldon and Dua (2023) are similar to ours in that they found a positive impact of subsidies over the years. However, a notable difference is that they observed this impact in the first year after introducing subsidies. He et al. (2023) investigated the effects of tax incentives (tax credits) on sales of PHEVs in the first six months after their introduction. The study found that the incentive had a positive effect as early as the first month after implementation and continued to have a positive impact until the fifth month. Although our analysis uses a more extended time window of years, making a direct comparison difficult, this result provides an interesting indication of the behavior of a policy's impact over time. In addition, Liu et al. (2023) identified that in China, strategies that jointly use purchase subsidies, purchase tax exemptions, and vehicle purchase restrictions can be effective in promoting EVs in the short term.

Ownership incentive policies did not demonstrate any effect over the years. Considering that this policy includes circulation tax, which in many countries is calculated based on CO_2 emissions, the substantial benefit brought by this policy to PHEV owners may be minimal. In addition, circulation tax seems to have a limited impact on the promotion of EVs, given that consumers tend to show a stronger preference for reducing the initial cost of the vehicle compared to annual or monthly charges (Gass et al., 2014).

Fig. 4 shows that the parallel trend assumptions are met for purchase incentive policies. As for ownership incentives, the assumption of parallel trends may not hold because the confidence intervals of the pre-event years −3 and −2 assume non-zero values. This may suggest that EV adoption behaviors diverged between countries even before incentive policies were implemented.

5.2. Baseline results

In this section, we present the results of TWFE and the event study. We then compare the results obtained with the results of the multi-period DID as presented in the previous section.

5.2.1. BEV registrations

Tables 6 and 7 present the TWFE and event study results obtained from equations (3) and (4) in panel A and the multi-period DID results in Panel B for the ownership and purchase incentive policies, respectively. We present the results of the dynamic effects over

Table 5
Dynamic marginal treatment effect of financial incentives policies on PHEV registration.

Even time	Ownership		Purchase	
	ATT	Overall ATT	ATT	Overall ATT
Year −6	0.7920 (6.4856)	−1.2111 (1.0944)	0.0265 (1.1007)	0.17 (0.1477)
Year −5	−2.3384 (1.1447)		−0.2068 (0.6725)	
Year −4	−0.8990 (0.5627)		1.6441 (1.2713)	
Year −3	1.6607 (0.8325)		−1.2887 (1.3649)	
Year −2	−1.0265** (0.2357)		0.0096 (0.4001)	
Year −1	0.6914** (0.1668)		−1.3898 (0.7254)	
Year 0	−0.3829 (0.8304)		−0.2225 (0.2127)	
Year 1	−1.5799 (1.3196)		0.5037 (0.3688)	
Year 2	−2.9733 (2.0921)		0.8131** (0.2567)	
Year 3	0.2964 (1.1267)		0.8816** (0.3614)	
Year 4	−0.1692 (1.5710)		−1.1258** (0.1943)	

Note: * p < 0.1, ** p < 0.05, *** p < 0.01. Robust standard errors are in parentheses.

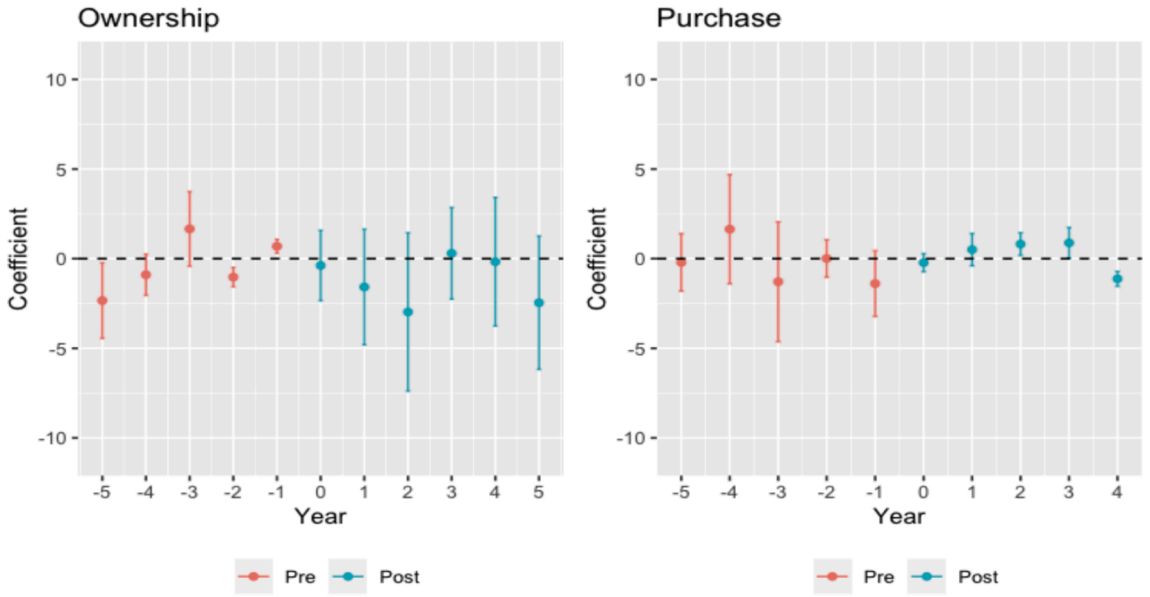


Fig. 4. Dynamic impact of Ownership and Purchase financial incentives policies on PHEV registrations.

four years of exposure to the policy after its implementation. In panel A of Table 6, the coefficient of the TWFE shows that ownership incentive policies have a positive and significant impact, resulting in an average increase of 80.3 % in the BEVs market share. This estimate is very different from the one obtained by the overall ATT that provides the average of the effects of the implementation of this policy approach on BEV registration in all groups of countries that implemented it, because the overall ATT was not significant. However, TWFE does not show robustness when exposure to the event occurs at different times and there is the presence of heterogeneity of the treatment effect (Sun and Abraham, 2021; Callaway and Sant'Anna, 2021). The dynamic effect obtained through the event study is not significant over the years. Panel B yields a similar result, indicating that the estimates obtained through the multi-period DID, presented in section 5.1.1, are consistent with the estimates of the event study.

The evaluation of our TWFE estimates (80.3 %) contrasts with similar research. Plötz et al. (2016) found that indirect incentives, including fuel and circulation tax exemptions, would increase the share of EV sales by around 30 %. Münzel et al. (2019) concluded that recurring incentives, among which circulation tax exemptions, could increase EV registrations by up to 35 % for every 1,000 euros additional tax benefit. However, these studies considered incentives other than circulation tax or fuel taxes. In addition, Plötz et al. (2016) assessed the number of indirect incentives, while Münzel et al. (2019) explored the magnitude of the incentives. Xue et al. (2021) focused exclusively on ownership incentives (binary variable) and concluded that these could lead to an increase in EV adoption of up to 1.8 %. These studies did not differentiate the impact of these incentives between BEVs and PHEVs.

Considering the TWFE coefficient in panel A of Table 7, our estimates suggest an average increase of 0.0125 % in the percentage of BEV registrations for every dollar made available for the purchase incentive policy. Therefore, 1,000 USD of this incentive could imply an average relative increase of approximately 12.5 % in BEV registration shares. The effectiveness of the policy approach is maintained only in the first year after exposure to it, leading to an average increase of 0.039 % in BEVs registrations. The estimates found in panel B show that the overall ATT has an impact twice as large as the TWFE and a lower significance level ($p < 0.05$). The dynamic ATT effects, in contrast to the results of the event study, extend for four years after exposure to the policy. Thus, both TWFE and multi-period DID results demonstrate an effectiveness in the implementation of the purchase incentive policy in boosting BEVs registration, although with different magnitudes and variation of the effect over the years.

Our results in the TWFE regression (12.5 %) align with previous studies and predictions about the impact of these incentives. Using

Table 6
Effects of ownership incentive policy on BEV registrations.

	Partially aggregated				Single parameter
Panel A: conventional TWFE					0.80266** (0.32518)
event study	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	0.000575 (0.000360)	0.000447 (0.000360)	0.000438 (0.000457)	0.000565 (0.000467)	
Panel B: multi-period DID overall ATT					0.3122 (1.1369)
dynamic effects ATT	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	0.0078 (0.7198)	0.8938 (1.0203)	0.8556 (0.8239)	0.2584 (1.0024)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. "e" indexes the length of exposure to the treatment. Robust standard errors are in parentheses.

Table 7
Effects of purchase incentive policy on BEV registrations.

	Partially aggregated				Single parameter
Panel A: conventional TWFE					0.000125** (0.000046)
event study	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	0.000390** (0.000162)	0.000179 (0.000196)	0.000056 (0.000276)	0.000250 (0.000292)	
Panel B: multi-period DID overall ATT					1.1347** (0.2185)
dynamic effects ATT	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	1.3720** (0.2086)	1.9136** (0.3648)	1.1567** (0.2877)	0.8312** (0.3301)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. "e" indexes the length of exposure to the treatment. Robust standard errors are in parentheses.

a country-fixed effects model, Plötz et al. (2016) concluded that a subsidy of 1,000 euros could increase the sales share of EVs by around 16 %. Using the same model, Münzel et al. (2019) found that a 1,000 euros rebate implies an average relative increase of approximately 8.1 % in EV registrations. Jenn et al. (2018) identified that a 10,000 USD tax credit or rebate could result in an average 26 % increase in EV registrations in the US. In a global analysis, Chandra (2022) found that the availability of subsidies could boost demand for BEVs by 5.7 %. Additionally, using FE regression, Shang et al. (2024) determined that a 1 % increase in purchase subsidies could increase EV sales by up to 1.36 % in Chinese cities.

5.2.2. PHEV registrations

Tables 8 and 9 present the results of the TWFE and event study in panel A and the results of the multi-period DID in panel B for the policies of ownership and purchase incentives, respectively. The results for the dynamic effects are provided for a four-year window of exposure to the policy after its introduction in the country. Panel A of Table 8 reveals that ownership incentive policies do not seem to drive the registration of PHEVs, since the coefficients of TWE and event study are not significant. These results are consistent with the multi-period DID analysis discussed in Section 5.1.2.

Table 9 shows the effects of the purchase incentive policy adoption on the registration of PHEVs. We verified the TWFE and event study coefficients in panel A, which was insignificant, and a similar result was found in panel B for the overall ATT. In contrast, panel B also shows that the dynamic effects ATT are significant, allowing us to see that the policy has a positive impact on the second and third years after its implementation, as discussed in section 5.1.2. The lack of significance in the conventional TWFE estimates compared to the multi-period DID estimates may reflect that TWFE gives more weight to the larger treatment groups (Goodman-Bacon, 2021), so if these groups are not significant, this may reduce the overall significance of the TWFE estimate.

The results of these tests reflect the disparity in incentives offered to BEVs and PHEVs (Hardman et al., 2017). Because BEVs generally have a higher acquisition cost than PHEVs, BEVs require more substantial financial incentives to compensate for this initial cost difference (Münzel et al., 2019). Hence, the research often shows that incentive policies have a more significant influence on BEV adoption than PHEV adoption (Neves et al., 2019; Chandra et al., 2022; Zheng et al., 2022). However, while our findings show ownership policy lacks significance in boosting PHEV registrations, Grandi (2020) found that circulation tax exemption for PHEVs in Norway and the Netherlands could spike adoption by 146 %. Similarly, Vassileva and Campillo (2017) showed that annual circulation tax exemptions could induce Norwegians to buy EVs. In the same vein, Hackbarth and Madlener (2013) concluded that removing these incentives could result in a negative impact on the German BEV and PHEV market. This difference with our results could arise because the previous studies analyzed the effect of these financial incentives in geographical contexts limited to one or two countries. Furthermore, in these countries, circulation tax exemptions for EVs are quite attractive (Ajanovic and Haas, 2016; Rietmann and Lieven, 2019). Lieven (2015) noted that tax exemptions could increase the promotion of EVs, including PHEVs, by up to 51 %, especially in high-tax countries.

Our findings in the TWFE regression on the purchase policy in the promotion of PHEVs corroborate the studies by Neves et al. (2019), Liu et al. (2021) and Chandra (2022), who did not observe any significance of these incentives in increasing in the market growth of these vehicles. However, they analyzed the policies together without distinguishing between purchase and ownership. In contrast to our findings, DeShazo et al. (2017) and Li et al. (2017a) show that financial incentives, such as rebates or tax credits, have

Table 8
Effects of ownership incentive policy on PHEV registrations.

	Partially aggregated				Single parameter
Panel A: conventional TWFE					0.40063 (0.38846)
event study	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	0.000124 (0.000253)	0.000070 (0.000358)	0.000268 (0.000360)	0.000627 (0.000418)	
Panel B: multi-period DID overall ATT					−1.2111 (1.0944)
dynamic effects ATT	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	−1.5799 (1.3196)	−2.9733 (2.0921)	0.2964 (1.1267)	−0.1692 (1.5710)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. "e" indexes the length of exposure to the treatment. Robust standard errors are in parentheses.

Table 9
Effects of purchase incentive policy on PHEV registrations.

	Partially aggregated				Single parameter
Panel A: conventional					
TWFE					−0.0000286
					(0.0000725)
event study	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
	−0.00004129	0.00019096	0.00001806	0.00021616	
	(0.000219)	(0.000262)	(0.000264)	(0.000383)	
Panel B: multi-period DID					
overall ATT					0.17 (0.1477)
dynamic effects	$e = 1$	$e = 2$	$e = 3$	$e = 4$	
ATT	0.5037 (0.3688)	0.8131** (0.2567)	0.8816** (0.3614)	−1.1258** (0.1943)	

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. "e" indexes the length of exposure to the treatment. Robust standard errors are in parentheses.

the potential to boost EV sales. However, the impact of this increase on sales may depend, among other factors, on the value of the incentives offered and the type of incentive, which possibly explains the difference between these results and ours. For example, DeShazo et al. (2017) demonstrated that by offering rebates of 2500 USD for BEVs and 1500 USD for PHEVs, sales can increase by up to 7 %. Li et al. (2017a) found that a federal tax credit of up to 7,500 USD for EV buyers had a substantial impact, contributing around 40 % of total EV sales.

5.3. Robustness checks

5.3.1. Placebo tests

To ensure that our results are induced by policy implementation and not cyclical or unobservable factors, so-called spurious causality (Zheng et al., 2022; Caldeira et al., 2023), we assign a random implementation date to the ownership and purchase incentive policies and observe whether the results obtained in section 5.1 change. We estimate 1,000 placebo regressions with the identical specification used in the multi-period DID regression in equation (9). In Fig. 5, the black line represents the cumulative distribution

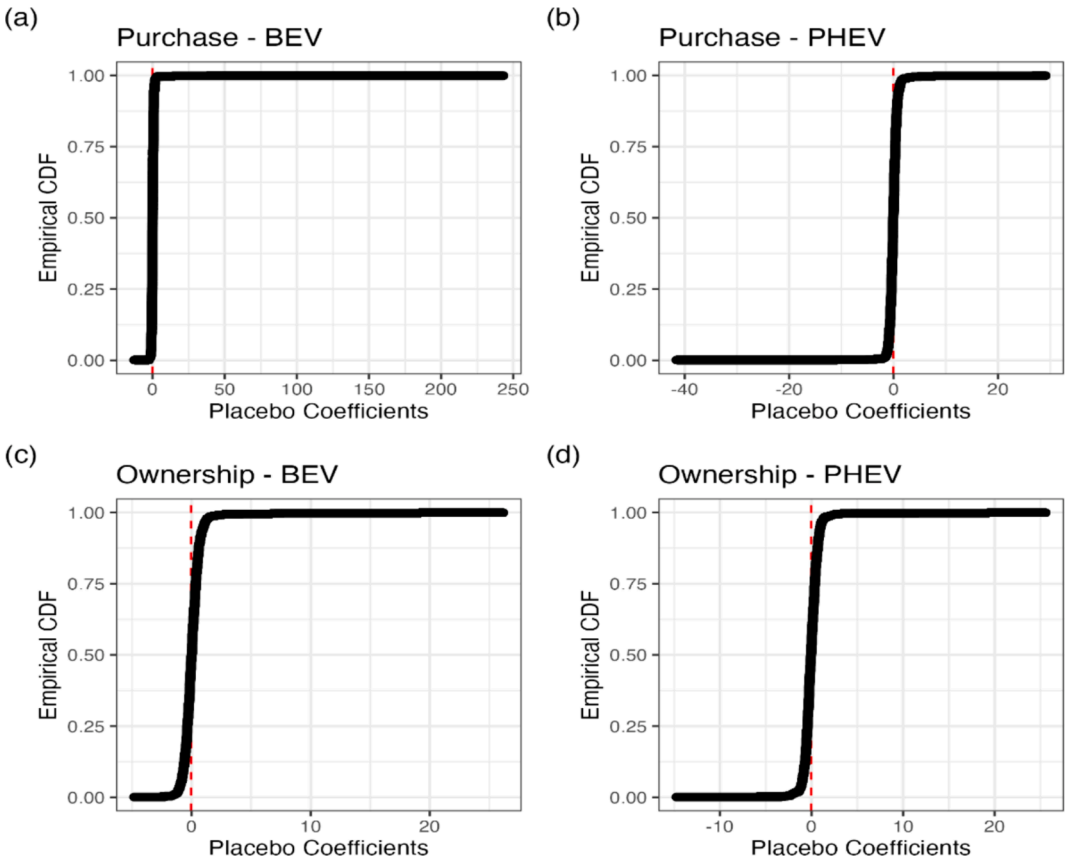


Fig. 5. Placebo Tests.

function (CDF) of the coefficients from the placebo regressions after implementing these 1,000 placebos estimates for purchase and ownership policies on BEV and PHEV registrations. The results obtained in our main specification presented in section 5.1 is represented at $x = 0$. We observe that the distribution of the dynamic effects ATT estimates is concentrated around zero. Therefore, the placebo variables showed no significant causal effect on the variable of interest. This result increases our confidence that our coefficients are not spurious.

5.4. Heterogeneity between countries

The previously discussed results provide evidence that purchase incentive policies positively influence the registration of BEVs and PHEVs in European countries. However, ownership policy did not have a significant effect in increasing BEV and PHEV registrations. In this section, we investigate the third research question regarding the impact of both policies in countries with different GDP levels, renewable energy consumption, and gasoline prices. We present only the estimates from the TWFE and event study because using the multi-period DID model requires a number of treatment and control units and periods before and after the intervention, which are not available in our sample. More importantly, we observed that the conventional TWFE produced results consistent with those found in the multi-period DID. The following subsections discuss the findings for each subsample.

5.4.1. Financial incentives and EV registration for different GDP per capita groups

Table 10 presents the summary results of the TWFE and event study regressions for BEVs and PHEVs registrations. The sample was divided into subgroups based on GDP per capita, with one group considered high (GDP above 31 k USD per capita) and another considered low (GDP below 31 k USD per capita). The choice of reference values to divide the sample was based on the median values. More specifically, when variables *p*-values are below 10 %, we adopt (+Y) for positive significance and (-Y) for negative significance. If the variables are not significant (*p*-values > 0.10), we use (N). For the case where the event study parallel trend hypothesis was not met, we use the symbol (0).

The results reveal some heterogeneity in the effect of ownership and purchase policies between the high and low GDP groups for registration of BEVs and PHEVs. The estimate of the average effect of ownership and purchase incentive policies in countries with different GDP levels obtained using TWFE indicates a positive impact on the registration of BEVs in countries with lower GDP per capita. This may be due to direct savings at the time of vehicle purchase and the annual tax exemptions and deductions brought about by these policies, which enable reductions in vehicle purchase and operating costs (Xue et al. 2021). Consequently, this renders BEVs more affordable in these countries. However, our results contrast with the findings of Harrison and Thiel (2017), Yong and Park (2017) and Alali et al. (2022), who found that financial incentive policies are more effective when GDP per capita is high. Alternatively, Alali et al. (2022) found that financial incentives may not be the primary driver of EV adoption in countries with lower GDP.

The event study shows no significant dynamic effect of the treatment of ownership and purchase incentive policies. Therefore, for this regression specification, we do not identify heterogeneity among the country groups.

5.4.2. Financial incentives and EV registration for different renewable consumption groups

Table 11 presents the estimates of the TWFE and event study regressions for the country groups divided based on renewable energy consumption, with one group considered high (consumption above 15 %) and one group considered low (consumption below 15 %). The results suggest heterogeneity in the effect of ownership and purchasing policies across country groups on BEV and PHEV registrations. More specifically, the TWFE estimate indicates that the average effect of implementing the ownership incentive policies is positive and significant for increased BEV registration in countries with lower renewable energy consumption. Similarly, this policy approach was significant for adopting PHEVs for the group of countries with high renewable energy consumption. Purchase incentive policies were positive and significant for BEVs in countries with higher renewable energy consumption. This could be due because countries with higher renewables consumption tend to set more restrictive environmental standards and have higher income (Kazemzadeh et al., 2022).

The estimates from the event study indicate that the effect of ownership and purchase incentive policies are not heterogeneous across groups of countries with different renewables consumption.

5.4.3. Financial incentives and EV registration for different gasoline price groups

Table 12 presents a summary of TWFE estimates and event study for country groups with different levels of gasoline prices, with

Table 10
Heterogeneity between countries with different levels of GDP.

		BEV				PHEV			
		Ownership		Purchase		Ownership		Purchase	
		static TWFE	event study	static TWFE	event study	static TWFE	event study	static TWFE	event study
GDP (High/Low)	Policy	N/+Y	N/N	N/+Y	N/ 0	N/N	N/N	, N/N	0/N
	GDP	N/N	N/N	N/N	N/N	+Y/N	+Y/N	+Y/N	N/N
	Renewable	N/N	N/N	N/N	N/N	−Y/N	N/+Y	−Y/N	N/N
	Gasoline price	N/-Y	N/-Y	N/-Y	N/N	−Y/N	−Y/N	−Y/N	N/N

Note: 'N': not significant; '+Y': it is positively significant; '-Y': it is negatively significant; '0′ parallel trends were not met.

Table 11
Heterogeneity between countries with different levels of renewable energy consumption.

		BEV				PHEV			
		Ownership		Purchase		Ownership		Purchase	
		static TWFE	event study	static TWFE	event study	static TWFE	event study	static TWFE	event study
Renewable (High/ Low)	Policy	N/+Y	N/N	+Y/N	N/N	+Y/N	N/N	N/N	N/0
	GDP	+Y/+Y	+Y/N	N/+Y	+Y/N	N/+Y	N/+Y	N/+Y	N/+Y
	Renewable	N/N	N/N	N/+Y	N/N	+Y/N	N/N	+Y/N	N/N
	Gasoline price	N/-Y	−Y/-Y	N/-Y	N/-Y	N/-Y	N/-Y	N/-Y	N/-Y

Note: 'N': not significant; '+Y ': it is positively significant; '-Y ': it is negatively significant; '0' parallel trends were not met

one group considered high (average prices above 1.68 USD/l) and another considered low (prices below 1.68 USD/l). The results identified in TWFE and event study regression were not significant, suggesting that there were no differential effects among these groups of countries on the adoption of BEVs and PHEVs.

6. Conclusion

In this work, we assess the impact of ownership and purchase financial incentive policies on the registration share of BEVs and PHEVs in European countries between 2012 and 2021. Our approach, multi-period DID, was effective in evaluating the impact of the policy as it considered its staggered implementation and identified the average treatment effect, highlighting differences in the exposure time of countries to the policy. In addition, multi-period DID enables us to address the issue of endogeneity by including multiple pre-intervention periods, thus controlling for pre-existing trends in the dependent variable between treatment and control groups.

Our first and second research questions sought to answer the effects of financial incentive policies on the market share of registered BEVs and PHEVs, as well as the effect of these policies over time. Our estimates suggest that ownership incentive policies do not significantly influence the adoption of BEVs and PHEVs. However, purchase incentive policies have contributed considerably to BEV adoption, possibly increasing them by over 113 % of adoption levels without such incentives. Meanwhile, the dynamic impact shows that purchase incentive policies take effect one year after its implementation, peak in the second year, and maintains their effect at least until the fourth year. Thus, the effect of this policy is maintained over time. For PHEVs, our estimates suggest that purchase incentive policies become effective in the second year after implementation, peaking in the third year, but showing a substantial decrease in the fourth year. Therefore, financial incentive policies appear to catalyze EV registration growth, but their impact as a public policy varies over time across policy types and EV types. To answer the third research question, we conducted a heterogeneity analysis. Our study identified heterogeneity between different groups of countries with respect to BEV registrations. Purchase incentive policies were significant only in countries with higher GDP per capita and higher renewable energy consumption. In contrast, the ownership incentive policies were significant only in countries with lower GDP per capita and lower renewable energy consumption.

Our results suggest a number of policy implications. First, policymakers might focus investments in purchase incentive policies to redirect them toward increasing the registration of BEVs. Other research indicates that in the absence of purchase incentives, consumers are more likely to buy PHEVs as they tend to focus on the initial price of the vehicle (Larson et al., 2015; DeShazo et al., 2017). Second, purchase and ownership incentive policies should be reviewed and monitored frequently to ensure their effectiveness. By conducting regular analysis, policymakers can identify changes in market behavior or technology that may affect the impact of the policies over time and make necessary adjustments to ensure that they remain practical and relevant. Third, governments must consider the context and country-specific factors in which the policy will be implemented to promote EV adoption. Countries with smaller GDPs may have fewer resources available to invest in EV market development, making it necessary to evaluate carefully the type of policy that will bring the most benefits. Similarly, countries with low renewable energy consumption may find it more challenging to achieve a more significant market share in EVs, which is one of the main prerequisites for their successful adoption (Yan, 2018). Thus, policymakers must carefully consider the factors that can influence the effectiveness of financial incentive policies for EVs.

Our research has some limitations that must be noted. First, using Callaway and Sant'Anna's (2021) multi-period DID method to evaluate the impact of incentive policies may present some limitations, such as the availability of data for various pre-treatment and post-treatment periods for the different groups of treated and untreated units. Therefore, a control group that is too small may violate the parallel trend assumption, leading to biased estimates of treatment effects or the inappropriateness of the model for estimating treatment effects. This prevented us from performing a heterogeneity analysis using this method. Second, the choice of the dummy variable may not be efficient enough to capture all the important characteristics of these policies. This limitation can be overcome by including other variables with more detailed policy information, such as incentive value, duration or eligibility criteria. Moreover, complementing the results obtained in the multi-period DID with a qualitative approach can help gain a more thorough understanding of the effect of the policies. Third, other factors not considered in our analysis, such as public charging infrastructure, environmentalism, socio-demographic factors, consumer preferences, and electric vehicle prices, may influence the results. Collecting additional

Table 12
Heterogeneity between groups of countries with different gasoline price levels.

		BEV				PHEV			
		Ownership		Purchase		Ownership		Purchase	
		static TWFE	event study	static TWFE	event study	static TWFE	event study	static TWFE	event study
Gasoline price (High/Low)	Policy	N/N	N/0	N/N	N/N	N/N	0/N	N/N	N/N
	GDP	N/N	N/N	N/N	N/+Y	+Y/N	+Y/N	+Y/N	N/N
	Renewable	N/N	N/N	N/N	N/N	N/N	N/+Y	N/N	N/N
	Gasoline price	N/-Y	N/-Y	N/-Y	N/-Y	−Y/N	−Y/N	−Y/N	−Y/-Y

Note: 'N': not significant; '+Y': it is positively significant; '-Y': it is negatively significant; '0' parallel trends were not met.

data and performing hypothetical scenarios or modeling incorporating different values and assumptions for the missing factors would be an excellent avenue for future work.

For future research, we suggest evaluating how financial incentive policies can impact the adoption of BEVs in the long term and investigating the effects of policies that were not considered in this study. Our research seeks to make a meaningful discussion on the effectiveness of financial incentive policies as a driver of EV registrations. Our research focused on Europe, but its findings may help policymakers in other countries or regions establish strategies to mitigate greenhouse gas reduction through passenger vehicle electrification and thus achieve a more sustainable road transport sector.

7. Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used DeepL in order to translate the original text of some paragraphs (or sections) from the first author's native language into English. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Edlaine Correia Sinézio Martins: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julien Lépine:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacqueline Corbett:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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