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Federal Transformation costs of e-mobility in Germany: Effectiveness and efficiency of EV incentives between 2015 and 2023

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ABSTRACT

This study evaluates Germany's federal electric vehicle (EV) incentive package, analyzing its impact on the automotive market, consumer purchase decisions, and environmental outcomes. Utilizing data from the German Ministry of Finance, Federal Motor Transport Authority, and Federal Office of Economics and Export Control, the research assesses new EV registrations, as well as federal total, specific, and CO_2 abatement costs from 2015 to 2023. Results show the environmental bonus significantly boosted EV adoption, with a 250% increase in subsidized vehicles between 2020 and 2021 and battery electric vehicles (BEV) comprising 18.3% of new registrations by 2023. Fiscal analysis uncovers combined costs of tax revenue shortfalls and subsidies at approximately EUR 17 billion, underscoring substantial financial commitments. Nonetheless, the incentives have significantly fostered EV adoption and environmental goals, achieving CO_2 savings of 3 million tons, excluding production emissions compared to assumed average petrol cars. Conclusively, Germany's EV incentives have effectively promoted electric mobility despite fiscal and societal challenges. These findings inform policy design, advocating for a balanced approach to innovation and societal impacts on electric mobility's progression.

1. Introduction

Within the partly contradicting landscape of environmental and transportation policies, the transition to electric vehicles (EVs) stands as a central strategy for defossilization and decarbonization. EVs play a crucial role in diminishing greenhouse gas (GHG) emissions from the transportation sector, positioning themselves as pivotal to worldwide efforts to reduce carbon footprints and tackle climate change. (Hausfather, 2019) However, such a shift towards EVs will only occur if governmental measures enforce such a development due to the highly developed and globally successful combustion-based transportation system. (IEA, 2023) Additionally, the path toward widespread EV adoption encounters numerous hurdles outside the "classical" transportation sector, such as heightened demands on electrical grids, capacity expansion of renewables, and a potential uptick in dependence on large-scale energy storage within a renewable electricity framework. (Exro, 2022).

In this complex environment, the impact of the government's financial support for EV mobility, intended to contribute to GHG savings, has not always yielded the expected results. To reduce GHG emissions within the transportation sector, the German federal government has progressively introduced a variety of incentives in recent years, including subsidies and tax breaks, specifically designed to encourage the adoption of EVs. (IEA, 2024; Ffe, 2023) Germany's strategic deployment of EV incentives over time has led to significant advancements in market penetration and the development of a comprehensive charging infrastructure. By 2023, the adoption rate of battery electric vehicles (BEVs) in new registrations reached 18.4 %,

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Abbreviations: BAFA, Federal Office for Economic Affairs and Export Control; BEV/PEV, Battery Electric Vehicle / Plug-In (electric) Vehicle; BMVI, Federal Ministry of Digital and Transport; BMWK, Ministry for Economic Affairs and Climate Action; CO_2, Carbon-Dioxide; DARP, German Development and Resilience Plan; EstG, Energy Tax Law; EV, Electric Vehicle; FCEV, Fuel Cell Electric Vehicle; GHG, Greenhouse Gases; HEV, Hybrid Electric Vehicle; ICE, Internal Combustion Engine; KBA, German Federal Motor Transport Authority; KraftStG, Motor Vehicle Tax Law; PHEV, Plug-in Hybrid Electic Vehicle; TRS, Tax Revenue shortfall; VAT, Value Added Tax.

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underscoring the effectiveness of these policy measures, but also raising questions about their long-term financial sustainability. (KBA, 2023).

1.1. Literature review

Demand-side fiscal policies are among the most used mechanisms to promote EV deployment. Several studies have indicated that while these policies can effectively boost EV adoption, they often entail significant financial burdens. (Sheldon et al., 2023; Langbroek et al., 2016; Sheldon and Dua, 2019; Baldursson et al., 2021).

For example, early evidence from light-duty vehicle markets in the U. S., Europe, and Canada suggests that promoting EV deployment through subsidies is costly, with high expenses associated with incentivizing the purchase of BEVs also called plug-in electric vehicles (PEV) within different studies. (Miess et al., 2022; Sheldon et al., 2023; Xing et al., 2021; Sheldon and Dua, 2019; Bennett and Isaac, 2023).

Furthermore, research within the European Union underscores that financial incentives - such as purchase subsidies and tax exemptions - remain critical drivers for EV ramp-up and deployment. Notably, countries with more robust financial support and well-developed charging infrastructure, such as Germany, exhibit higher EV adoption rates. (Martins et al., 2023).

Previous studies have emphasized the substantial costs associated with EV subsidies. In the U.S., direct state and federal subsidies for EVs average $8,984 per vehicle over ten years. These figures are considerably higher when accounting for hidden subsidies and regulatory credits, suggesting that without nearly $22 billion in federal and state support, the average cost of owning an EV would be significantly higher. (Bennett and Isaac, 2023) Additionally, the total cost of subsidies for EVs and the necessary infrastructure, such as charging stations, is immense. For example, the costs in California alone could exceed $100 billion by 2030. (Lesser, 2018).

Several studies suggest that the impact of regulatory credits and socialized infrastructure costs further complicates the economic assessment of EV policies. Regulatory credits, such as those associated with Corporate Average Fuel Economy (CAFE) standards and the socialization of infrastructure costs, significantly reduce the apparent cost of EVs. (Bennett and Isaac, 2023; Martins et al., 2023; Audouin and Finger, 2019) For instance, regulatory credits can provide approximately $27,881 in benefits per vehicle for EV manufacturers, while infrastructure costs add an average of $11,883 in socialized costs per EV over ten years. (Bennett and Isaac, 2023) In Germany, significant purchase subsidies and tax benefits have rapidly increased EV registrations, with the market share of electric vehicles (including plug-in hybrids) reaching approximately 26 % by 2021, up from just 3 % in 2019. (Audouin and Finger, 2019) However, the high costs of existing federal subsidies, as observed in the U.S., raise concerns about their long-term viability, with the average cost per additional PEV purchase estimated at around $35,601. (Sheldon and Dua, 2019).

1.2. CO_2 emissions and abatement costs

Still, EV incentive programs have had a positive impact on reducing emissions. In Germany, for instance, the incentive programs have led to an estimated reduction of approximately 1.2 million tons of CO_2 emissions per year by 2021, contributing significantly to the country's climate goals. (Sheldon and Dua, 2019) Recent studies also indicate that emissions in Germany's transport sector were reduced by 1.8 million tons between 2022 and 2023, primarily due to the increased adoption of EVs in road transport. (Umweltbundesamt, 2023).

Several studies have also explored the abatement costs associated with EV subsidies. (Audouin and Finger, 2019; Sheldon and Dua, 2019; Sheldon et al., 2023) For example, in the U.S., the cost per gallon of gasoline saved through these subsidies was calculated at $5.11, highlighting the economic burden of such incentive programs, especially when not targeted effectively. (Sheldon and Dua, 2019) In Germany, the cost-effectiveness of these subsidies is debated, with estimates suggesting that the cost per ton of CO_2 abated ranges between €600 and €1,000, depending on the specific vehicle and usage patterns. (Audouin and Finger, 2019) This is relatively high compared to other countries like Norway and Sweden, where the cost per ton is lower due to more aggressive adoption rates and better infrastructure. A recent study examining 11 countries, including Germany, found significant variation in the (abatement) cost per ton of CO_2 emissions avoided through EV subsidies, with costs ranging from $739 to $1,600 per ton. (Sheldon et al., 2023).

1.3. Research gaps

While prior studies have explored the costs and benefits of demand-side EV subsidies, several critical gaps remain unaddressed. Notably:

- Many analyses focus on purchase subsidies and tax exemptions but fail to comprehensively account for supply-side costs, such as infrastructure investments, research funding, and tax revenue shortfalls. This limits the ability to fully evaluate the financial trade-offs of these policies and their long-term impact on public budgets.
- Temporal analyses of EV policy costs are limited, with few studies examining how these expenses evolve over time and how they influence long-term policy effectiveness. Without this perspective, policymakers lack insights into whether current incentives can sustain market growth without disproportionately straining financial resources.
- The distribution of federal costs among different user cases, such as private versus company cars, and across drivetrain technologies, such as BEVs and plug-in hybrid electric vehicles (PHEVs), remains underexplored. This gap makes it difficult to tailor policies to specific market segments and ensure equitable distribution of benefits.
- Although (Bennett and Isaac, 2023) provides valuable insights by including tax revenue shortfalls, the lack of methodological transparency and U.S.-centric focus limits its applicability to Germany. In contrast, (Sheldon et al., 2023) provides a robust methodological framework but focuses narrowly on PHEVs and excludes BEVs and fuel cell electric vehicles (FCEVs).

1.4. Research Objectives

This research aims to provide a detailed assessment of Germany's EV incentive programs from 2016 to 2023, focusing on:

- Quantifying the federal costs associated with various EV incentives, including purchase premiums, tax revenue shortfalls, and infrastructure subsidies.
- Evaluating the environmental benefits of these programs, particularly CO_2 emission reductions achieved during the study period.
- Calculating CO_2 abatement costs to assess the efficiency and economic viability of the incentives.

Addressing the need for quantitative analysis, this research offers a foundation for discussions on EV incentives' rationale, effectiveness, and financial implications. It scrutinizes the costs and outcomes of policy choices, aiming to clarify the debate on EV market expansion costs in Germany and potentially assist other countries in policy formulation. Structured to offer a clear pathway through the examination of Germany's EV incentives, the paper outlines the assessment methodology first, then analyzes the results and concludes with the study's implications. It aims to rationalize the political and public discourse on EV incentives by providing a data-driven perspective on their costs, benefits, and wider impacts.

While this study focuses on the financial costs and CO_2 emissions associated with EV incentives from a government perspective, it acknowledges that other critical dimensions, such as equity, accessibility, and social acceptance, also play significant roles in the success of EV policies. These aspects, however, fall outside the scope of the present analysis and represent valuable avenues for future research.

2. Assessment methodology

The methodology employed in this study seeks to provide both a quantitative and qualitative evaluation of the costs associated with EV incentives in Germany. The analysis focuses on unit-cost allocation and the determination of CO_2 abatement costs, employing a hypothetical substitution of petrol cars to estimate CO_2 emissions. This approach facilitates a deeper understanding of CO_2 abatement costs from a macroeconomic perspective, highlighting the role of governmental interventions in reducing these costs for consumers. The study aims to shed light on the broader economic effects of EV incentives, demonstrating their contribution to the reduction of CO_2 emissions within the transport sector.

This study builds on the methodologies employed by (Bennett and Isaac, 2023) and (Sheldon et al., 2023), aiming to integrate their strengths while addressing their limitations. While (Bennett and Isaac, 2023) incorporates a wide array of cost positions, such as tax credits, purchase premiums, and tax revenue shortfalls, it lacks transparency regarding the calculation methods. Furthermore, Bennett's study is specific to the U.S. market, which does not fully account for the unique characteristics of Germany's EV incentives. Nevertheless, the inclusion of major cost elements aligns with the scope of our analysis.

(Sheldon et al., 2023) offers a more detailed methodological insight and includes Germany as a study focus. However, it primarily concentrates on plug-in hybrid electric vehicles (PHEVs), excluding battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), even though the latter plays a minor role in the current market. Additionally, (Sheldon et al., 2023) does not consider critical federal costs beyond purchase premiums, such as tax revenue shortfalls and other indirect costs.

This study seeks to combine the advantages of both approaches. Similar to (Bennett and Isaac, 2023), it incorporates the most relevant cost positions, while also presenting a comprehensive methodology tailored to Germany, as emphasized by (Sheldon et al., 2023). Our approach enhances granularity by leveraging detailed data on fleet composition, subsidies, and cost allocation. This includes differentiated analyses of charging infrastructure costs, tax-revenue shortfalls, and distinctions between private and company cars, as well as between BEVs and PHEVs. By addressing these gaps, this study provides a more nuanced understanding of the financial implications and effectiveness of EV incentives across different segments. Table 1 provides a comprehensive overview of the methodological differences and strengths between (Bennett and Isaac, 2023), (Sheldon et al., 2023), and the current study, highlighting their respective focus on market regions, methodological transparency, and the breadth of cost positions considered.

Table 1
Comparison of Methodologies for Evaluating EV Incentives.

Aspect	(Bennett and Overcharged, 2023)	Sheldon et al. (2023)	Our Study
Market Focus	U.S. market	Several Countries	Germany
Transparency of Methodology	Low (calculation details not provided)	Moderate (methodology partially detailed)	High (comprehensive methodological presentation)
Cost Positions Considered	Broad (e.g., tax credits, purchase premiums, tax revenue shortfalls)	Limited (focuses on purchase premiums)	Broad (e.g., tax credits, purchase premiums, tax revenue shortfalls, infrastructure costs)
Vehicle Types Included	BEVs and PHEVs	PHEVs only	BEVs, PHEVs, HEVs and FCEVs
Tax Revenue Shortfalls Considered	Yes	No	Yes
Relevance to Germany	Not relevant (U. S.-specific context)	Highly relevant (German context)	Highly relevant (tailored to German EV incentives)

2.1. Data

This study rests on comprehensive data collection, targeting several pivotal sources to construct a detailed picture of the EV incentive landscape in Germany. The primary data sources (BMF, 2015; BMF, 2017; BMF, 2019; BMF, 2023; BMF, 2021a) provide in-depth data about the costs associated with various incentives. Additionally, registration data (KBA, 2015–2023) offering insights into the market uptake of EVs following these incentives. Data about the environmental bonus was retrieved from (BAFA, 2023). The study primarily utilizes publicly available data and individually requests data (BMI, 2005). The exception is the microdata dataset (KBA, 2015–2023). Appropriate measures are being taken to ensure the confidentiality and ethical use of this data.

The research is primarily descriptive and analytical, focusing on evaluating the current state and impacts of EV incentives. The approach is inductive, relying on data collection and analysis to develop an understanding of the effectiveness and economic implications of these incentives. Therefore, it integrates quantitative analysis of subsidy costs, vehicle registrations, and environmental benefits with qualitative assessments of the broader economic and policy implications.

Another critical component of our data collection is the analysis of costs related to the environmental bonus, which is informed by inquiries made by political parties. This aspect is particularly significant, given the discrepancies often observed in data sources, especially concerning the costs for charging infrastructure and the environmental bonus. (German Bundestag, 2021; German Bundestag, 2022a; German Bundestag, 2022b).

2.2. Assessment approach

The overall assessment approach, delineated in Fig. 1, focuses on examining and analyzing the transformational costs, or federal market ramp-up costs, arising from Germany's incentive package for electric vehicles (EVs). This study aims to provide a macroeconomic analysis that highlights the broader impacts of EV incentives on federal expenditures, while differentiating this perspective from the microeconomic view typically adopted in customer-focused analyses.

From a **macroeconomic perspective**, the research quantifies all federal expenses tied to the identified incentives, drawing from the respective subsidy data (BMF, 2015; BMF, 2017; BMF, 2019; BMF, 2021a; BMF, 2023). These costs are categorized into:

- **Explicit Subsidies**, such as environmental bonuses, are provided directly to EV buyers.
- **Market Enablers**, including subsidies for e-mobility development and charging infrastructure, which are pivotal for supporting the adoption of EVs by building the necessary ecosystem for their operation and growth.
- **Implicit Costs**, such as federal tax revenue shortfalls resulting from tax exemptions and benefits for EVs.

Fig. 1 also illustrates the connection between macroeconomic and microeconomic perspectives. For example, subsidies for EV purchases appear as expenses in the federal budget balance sheet (macroeconomic costs), but the same subsidies represent cost reductions or income for eligible customers (microeconomic benefits). While customer-focused studies often adopt a practical perspective, treating tax credits or subsidies as incentives to lower individual costs, this study examines these measures as part of the broader economic landscape. This distinction

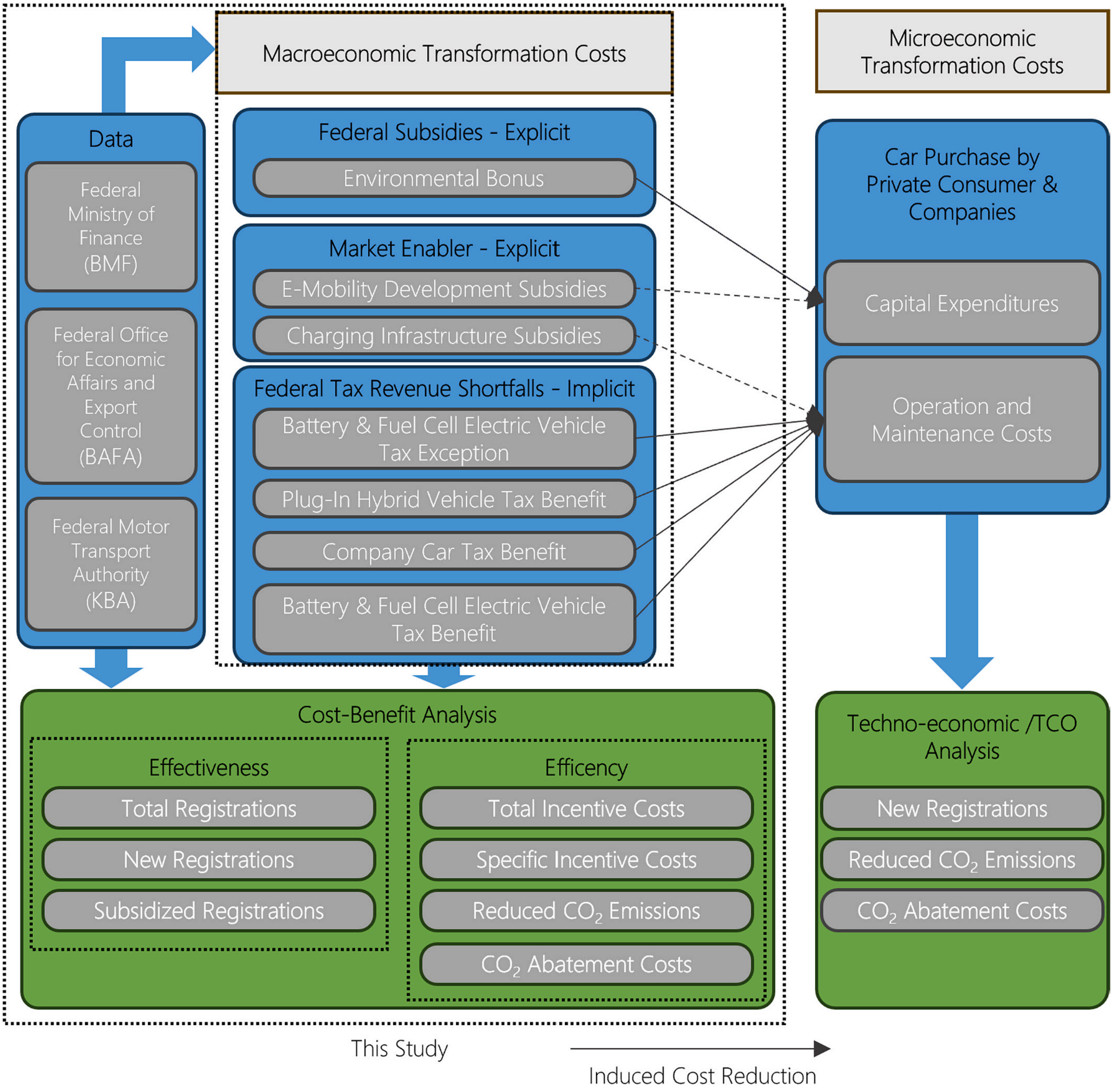

Fig. 1. Scope of this study macro-economic approach compared to other micro-economic assessment studies in the field.

highlights the unique contribution of the macroeconomic lens in understanding the systemic impacts of EV incentives.

Role of Market Enablers in Bridging Perspectives: Market Enablers, such as subsidies for charging infrastructure and e-mobility development, play a critical role in connecting the macroeconomic and microeconomic perspectives. From a macroeconomic viewpoint, these investments are essential federal expenditures aimed at fostering the growth of the EV market by addressing structural barriers, such as insufficient charging infrastructure. From a microeconomic perspective, the availability of charging infrastructure reduces practical barriers for individual EV owners, indirectly improving the perceived value and utility of EV ownership. This dual impact underscores how market enablers bridge the gap between macro-level policy goals and micro-level consumer incentives, further highlighting their importance in the broader assessment of EV policies.

The methodology incorporates cost allocation methods, distributing cost shares across each vehicle according to registration year, powertrain, and user type. This differentiation allows the study to analyze costs and benefits at both aggregate and segment-specific levels, distinguishing between private and company-owned cars.

The analysis involves several key steps designed to incrementally build an understanding of EV incentives and their implications:

- **Identification of Federal EV Incentive Programs**: The first step is to identify and categorize the various federal programs that incentivize EV adoption, including direct subsidies, tax incentives, and market enablers.
- **Quantification of Federal Costs**: The costs incurred by the federal government in implementing these incentive programs are

quantified. This encompasses both direct subsidies provided and the shortfall in tax revenues due to these incentives.

- **Analysis of EV Registrations**: A critical aspect is to gauge the effectiveness of these incentives in promoting EV adoption. This is achieved by analyzing the number of new registrations and distinguishing between subsidized vehicles and the total fleet in the German car market.
- **Quantifiable Assessment and Cost Allocation**: A quantifiable assessment of the federal costs per vehicle is undertaken, involving developing allocation keys for each cost position.
- **Definition of Use Cases, Scenarios, and Assumptions**: Scenarios are defined to estimate specific costs and CO_2 abatement costs, building a robust framework for assessing the broader economic implications.

Additionally, the methodology encompasses a qualitative assessment of variables not directly quantifiable within the study's scope, such as broader societal impacts and equity considerations. This qualitative analysis complements the quantitative data, broadening the understanding of the incentives' broader implications.

2.2.1. Cost allocation

The study advances to a quantifiable assessment and cost allocation phase, where it develops allocation keys to apportion federal costs per vehicle. This assessment involves a nuanced breakdown by registration year, powertrain technology, and user type (personal or company car), fostering a comprehensive understanding of the cost distribution. Thus, a matrix is created to examine four specific cases, delineating between private-owned and company-owned cars and further between PHEVs and BEVs and fuel cell electric vehicles (FCEV).

Equation (2–1) defines the Total Incentive Costs (*TIC*) as the aggregation of all Annual Incentive Costs (AIC_a) from the years 2015 to 2023, summing up the incentives per year. This equation provides a snapshot of the government's expenditure on EV incentives over time. IC_a are the Total Annual Incentive Costs further broken down based on equation (2–2), accounting for all powertrains, user cases, and incentives. It computes the total by summing the quotient of each applicable incentive ($IC_{a,i,j}$) and its corresponding allocation key ($AK_{a,i,j}$) (Table 5).

Total Incentive Costs:

$$TIC = \sum_{a=2015}^{2023} AIC_a = \sum_{a=2015}^{2023} \sum\nolimits_i IC_{a,i} \tag{2.1}$$

Annual Incentive Costs:

$$IC_a = \sum\nolimits_j \sum\nolimits_i \frac{IC_{a,i,j}}{AK_{a,i,j}} \tag{2.2}$$

2.2.2. CO_2 emissions

To assess the environmental impact of EV incentives in Germany, the CO_2 emission savings are calculated. This is realized by a series of equations designed to quantify the reduction in CO_2 emissions attributable to the adoption of incentivized EVs.

Equation (2–3) delineates the method for calculating the total annual CO_2 emission savings (ΔeCO_2), aggregating the sum of annual delta CO_2 emission savings (ΔeCO_{2_a}).

Total Annual CO_2 Emission Savings:

$$\Delta eCO_2 = \sum\nolimits_a \Delta eCO_{2_a} \tag{2.3}$$

Building on this, equation (2–4) calculates the annual CO_2 emission savings determined by contrasting the reference emissions ($eCO_{2_{a,Ref}}$) from a hypothetical scenario involving substituted petrol cars with the actual emissions from incentivized EVs ($eCO_{2_{a,EV}}$). This approach allows for a direct comparison between the emissions that would have been generated by traditional petrol internal combustion engine (ICE) vehicles and those from the incentivized EV fleet.

Annual CO_2 Savings:

$$\Delta eCO_{2_a} = eCO_{2_{a,Ref}} - eCO_{2_{a,EV}} \tag{2.4}$$

Equation (2–5) outlines the calculation of annual CO_2 emissions from vehicle operation ($eCO_{2_{a,operation}}$). This equation factors in the number of subsidized vehicles by year and powertrain ($NSV_{a,j}$), their average consumption (Con_j), the transport power (*TP*), and the emissions factor of each power source (EF_j), thereby providing a detailed account of operational emissions (also called tailpipe emissions).

CO_2 Emissions
(Operation):

$$eCO_{2_{a,operation}} = \sum\nolimits_j NSV_{a,j}\ Con_j\ TP\ EF_j \tag{2.5}$$

Finally, equation (2–6) calculates the production emissions based on the multiplication of the number of subsidized vehicles ($NSV_{a,j}$) by the average production emissions per vehicle for each powertrain ($eCO_{2_{j,Production}}$) dived by the average lifetime of a vehicle (T). This equation extends the scope of this assessment to include the CO_2 emissions incurred during the manufacturing phase of EVs, offering a more holistic understanding of their total environmental footprint.

CO_2 Emissions (Production):

$$eCO_{2_{a,production}} = \sum\nolimits_j NSV_{a,j} \frac{eCO_{2_{j,Production}}}{T} \tag{2.6}$$

2.2.3. CO_2 abatement costs

In evaluating the efficiency of electric vehicle (EV) incentives, a critical metric employed is the CO_2 abatement costs. This metric offers a macroeconomic perspective on the costs associated with reducing CO_2 emissions, distinct from microeconomic considerations such as business or personal abatement costs.

Equation (2–7) calculates the annual marginal abatement CO_2 costs ($MAC_{CO_{2,a}}$), which quantify the reduction in CO_2 abatement costs for consumers facilitated by federal subsidies and tax revenue shortfalls. This is determined by dividing the annual CO_2 emissions savings ($\Delta eCO_{2_a,j}$) by the corresponding eligible incentives ($IC_{a,i}$), aggregating across all powertrains (*j*) and incentives (*i*). This equation encapsulates the cost-effectiveness of the incentive programs in achieving CO_2 reductions.

Annual CO_2 Abatement Costs:

$$MAC_{CO_{2,a}} = \sum\nolimits_j \sum\nolimits_i \frac{\Delta eCO_{2_a,j}}{IC_{a,i}} \tag{2.7}$$

3. EV incentive programs in Germany

The transition towards electric mobility in Germany from 2014 to 2023 was significantly influenced by a series of market-based incentives aimed at consumers and as well as non-marked-based manufacturers (Schulthoff et al., 2022). Table 2 presents an overview of Germany's various incentives for electric vehicles (EVs) by listing the various incentives, their applicability, and their respective time limits for BEVs, FCEVs and PHEVs. Here, the incentives are subdivided into three main types:

- tax revenue shortfalls (also known as net tax loss),
- subsidies, and
- market enablers.

Key aspects include significant long-term tax reductions for BEV and FCEV. Additionally, the table illustrates the substantial support for market enabling by developing charging infrastructure and funding research and development in e-mobility. The varying expiration dates of these incentives reflect the dynamic and adaptive approach of Germany's policy landscape in response to evolving technological and

Table 2

Overview of federal incentives for e-mobility of cars in Germany and deadlines, based on (BMF, 2023; BMF, 2015; BMF, 2017; BMF, 2019; BMF, 2021a). Various deadlines occur if several incentive programs are summarized in a category.

Incentive Type	Designation	BEV	FCEV	PHEV
Tax revenue shortfalls	Company Car Tax Reduction	–———————— 31.12.2030 –————————		
	EV Vehicle Tax Exemption	31.12.2025	31.12.2025	–
	EV Vehicle Tax Reduction	Unlimited	Unlimited	–
	PHEV Vehicle Tax Exemption	–	–	31.12.2025
Purchase	Purchase Premium (Environmental Bonus)	18.12.2023	18.12.2023	31.12.2022
Market Enabler	Charging Infrastructure Subsidies	–———— various, max. 31.12.2025 –————		
	E-mobility R&D Funds	–———— various, max. 31.12.2025 –————		

market conditions.

3.1. *Tax reductions and tax revenue shortfalls*

This chapter examines the German government's implicit incentives for electric and hybrid vehicles, which occur as tax revenue shortfalls (TRS) and focus on tax reductions and exemptions aimed at promoting sustainable mobility and reducing environmental impact.

3.1.1. *Company-owned car tax reduction*

The tax reduction for company-owned cars is defined under the German Income Tax Act (EstG) (Bundesministerium für Justiz, 2020; BMF, 2023) reducing the taxable benefit for the private use of a company-owned car for BEV, FCEV, and PHEV. Starting from the 2019 tax period, the taxation of private use of such vehicles has been significantly lower compared to conventional vehicles. The taxable base being the gross list price of the vehicle is set at either a quarter or half, depending on the vehicle's characteristics (BMF, 2023). This incentive has no planned reduction (degression) over time, although the minimum requirements for externally rechargeable hybrid electric vehicles are expected to increase gradually (BMF, 2020; BMF, 2023).

3.1.2. *EV vehicle tax exemption*

The EV vehicle tax exemption is governed by § 3d of the Motor Vehicle Tax Act (KraftStG) (Bundesministerium für Justiz, 2002). This tax exemption applies to newly registered pure electric vehicles (zero-emission vehicles) and those that have been converted to electric. For vehicles being first registered between May 18, 2011, and December 31, 2025, as well as for conversions made between May 18, 2016, and December 31, 2025, the tax exemption is granted for a maximum of ten years, ending no later than December 31, 2030 (Bundesministerium für Justiz, 2002; BMF, 2023). Following the expiration of the tax exemption period, these vehicles are subject to a reduced rate of taxation (section 3.1.3). This continued incentive ensures ongoing support for the use of electric vehicles beyond the initial exemption period (Bundesministerium für Justiz, 2002; BMF, 2023). The financial responsibility for this tax exemption lies entirely with the federal government bearing 100 % of the cost (BMF, 2023).

3.1.3. *EV vehicle tax reduction*

The EV vehicle tax reduction is a 50 % reduction in the motor vehicle tax for pure electric vehicles (zero-emission vehicles) (Bundesministerium für Justiz, 2002) paid to 100 % by the federal government (BMF, 2023). Newly registered and converted pure electric vehicles are also eligible for a time-limited tax exemption. However, the impact of this 50 % tax reduction has been somewhat limited so far because most electric vehicles currently in use are still benefiting from the full tax exemption outlined in section 3.1.2. Thus, the 50 % reduction has not yet been widely applied.

3.1.4. *PHEV vehicle tax exemption*

The PHEV Vehicle Tax Exemption is legislated also under the Motor Vehicle Tax Act (KraftStG) and regulates tax exemptions for particularly emission-reduced passenger cars (PHEV), but not zero-emission vehicles (i.e., BEV and FCEV). This regulation is specifically designed for vehicles with a first registration date up until December 31, 2024 (Gesetze im Internet, 2002; BMF, 2023). This regulation is time-limited; it will expire / phasing out on December 31, 2025. This tax exemption is fully financed by the federal government (BMF, 2023).

3.2. *Purchase incentive: Environmental bonus subsidy*

The environmental bonus program is primarily funded through the Federal Ministry for Economic Affairs and Climate Action (BMWK) (BMVU, 2021; BMF, 2023). Additionally, this program has seen co-financing from regional governments and/or the EU. Notably, the innovation premium doubling the federal share of the environmental bonus was a key measure within the German Recovery and Resilience Plan (DARP) between 03.06.2021 and 31.12.2022 (BMF, 2021b; BMF, 2023). This subsidy is provided for the purchase and leasing of electric passenger cars and light commercial vehicles. This grant is only applicable when the automotive manufacturer offers a discount at least equal to the federal contribution to the net list price of the base model (BAFA list price). During the lifetime of this program, manufacturers matched the federal contribution by paying 50 % of the Environmental Bonus. During the Innovation Premium period, their share was reduced to one-third, partly to avoid penalties related to CO_2 emission limits (European Commission, 2023; Ecomento, 2023b).

Initially established in 2016 as part of a package of measures to promote electromobility, the environmental bonus has undergone several changes. As of January 1, 2023, the program was planned to be limited until the end of 2024 and structured to decrease over time. Additionally, the subsidy for PHEVs was discontinued. However, due to a significant budget shortfall, on December 13, 2023, it was announced that subsidies for electric cars would be discontinued earlier than planned (ZDF, 2023; German Government, 2023).

Since 2020, the automotive industry has been subject to stricter CO_2 regulations, necessitating an expansion of electric vehicle offerings or facing penalties. The anticipated and observed surge in applications towards the end of 2022, spurred by the cessation of PHEV funding and the degressive design of the subsidies from 2023, resulted in a record number of nearly 230,000 applications in December 2022. Following a subsequent decline in January 2023, application numbers have been slowly but steadily recovering as of mid-March 2023 (Ecomento, 2023b).

This subsidy program has played a crucial role in accelerating the transition to electric vehicles in Germany. The abrupt end of the funding in December 2023 due to budgetary constraints marks a significant shift in the government's approach to incentivizing electromobility. The evolution of the environmental bonus is shown in Table 3.

3.3. *Market-enabler incentives*

Germany's approach to accelerating e-mobility further contains several explicit incentives, such as direct subsidies, grants, development funds for car manufacturers, and deployment of infrastructure. These incentives function as a market enabler for the e-mobility market ramp-up and are additionally relevant to maintaining the car manufacturing industry within Germany.

Table 3
Evolution of environmental bonus subsidy in EUR (€).

Date	Eligible Vehicles	Subsidy Amount	Notes
18. May 2016	BEVs, FCEVs, PHEVs	€ 2,000 for BEVs and FCEVs, € 1,500 for PHEVs	Introduction environmental bonus (BMVU, 2021; BMWK, 2016)
1. Sep. 2018	BEVs, FCEVs, PHEVs	€ 2,000 for BEVs and FCEVs, € 1,500 for PHEVs	Introduction WLTP Test Cycle Removing non-eligible PHEVIntroduction of subsidy for Acoustic Vehicle Alert System (DeWiki, 2024)
Nov. 2019	BEVs, FCEVs, PHEVs	€ 3,000 for BEV/FCEV ($\leq$€ 40,000)€ 2,250€ for PHEV ($\leq$€ 40,000)€ 2,500 for BEV/FCEV (€ 40,000 – € 65,000)€ 1,875 for PHEV (€ 40,000 – € 65,000)	Raise of Environmental Bonus (DeWiki, 2024)
3. Jun 2020	BEVs, FCEVs, PHEVs	€ 6,000 for BEV/FCEV ($\leq$ € 40,000)€ 4,500€ for PHEV ($\leq$ € 40,000)€ 5,000 for BEV/FCEV (€ 40,000 – € 65,000)€ 3,750 for PHEV (€ 40,000 – € 65,000)	Introduction of Innovation Premium (doubling federal subsidy) until 31.12.2022 PHEV $>$ 50 gCO_2/km no EV range requirement PHEV $<$ 50 gCO_2/km EV range requirement: 2022: 60 km, 2025: 80 km (BMWK, 2018; DeWiki, 2024)
2023	BEVs, FCEVs	€ 2,250 ($<$ € 40,000) and€ 1,500 (€ 40,000 – € 65,000) used Cars: € 1500	From 01.09.2023, only private individuals can apply for the bonus. Small businesses and non-profit organizations might be exceptions.(DeWiki, 2024)
09. Sep 2023	BEVs, FCEVs	No changes	End of subsidies for company cars (German Government, 2023)
18. Dec. 2023	–		End of environmental bonus (German Government, 2023)

3.3.1. *Charging infrastructure funds*

The primary goal of these subsidies is to initiate the development of a comprehensive and demand-oriented charging infrastructure for electric vehicles across Germany. The foundation for these subsidies is laid out in various funding guidelines and legal frameworks outlined exemplarily below (Nationale Leitstelle Ladeinfrastruktur, 2023).

- The funding directive for public charging infrastructure for electric vehicles initiated by the Federal Ministry of Transport and Digital Infrastructure was initially established in February 2017 and later amended in June 2017 (BMVI, 2021a).
- The funding directive "Local charging infrastructure" has been published in March 2021 (BMVI, 2021b).
- The funding directive for charging infrastructure at residential buildings was established in October 2020 (BMVI, 2020).
- The funding directive for publicly accessible charging infrastructure for electric vehicles has become into force in July 2021 (BMVI, 2021a).
- The funding directive for non-publicly accessible charging stations for electric vehicles for businesses and municipalities has become valid in November 2021 (BMVI, 2021c).

These directives provide primarily grants. They are also recognized as EU aid, complying with the De-minimis regulation for certain directives (BMF, 2023; BALM, 2022). The subsidies are categorized as productivity aids. The various directives have different expiration dates, extending from June 2021 for the earliest directive to December 2025 for the latest one.

From an economic standpoint, the operation of charging infrastructure is not yet self-sustaining due to high investment and operational costs versus relatively low income from electricity sales during the currently ongoing ramp-up phase. This is attributed to the low number of vehicles and the resulting underutilization of the charging infrastructure. Against this background, the subsidies are designed to address this market failure in the nascent electric mobility sector (e.g., the average utilization of public charging infrastructure in Germany was 11.6 % in 2023, peaking at 25 % during high-demand times (BDEW, 2023)).

3.3.2. *E-mobility R&D (research and development) funds*

The overarching goal of these measures is to position Germany as a leading market and provider in electromobility. By 2030, the aim is to have 15 million fully electric passenger cars and 1 million public charging points. These ambitious targets are to be achieved through innovations in vehicle technology, an expansion of vehicle and infrastructure offerings, and the development of synergies between mobility and energy systems, including controlled and bidirectional charging. (BMF, 2023).

The legal groundwork for such R&D measures is established through various directives.

- A joint funding initiative initiated in February 2021 by the Federal Ministry for Economic Affairs and Climate Action and the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety for research and development in the field of electromobility.
- Several funding calls from the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety to promote projects in electromobility, including the electrification of vehicle fleets in the health and social services sector.
- The technology competition "ICT for Electromobility" focuses on intelligent applications for mobility, logistics, and energy, as well as economic applications and infrastructures for electric commercial vehicles (BMF, 2023).

Evaluations of the electromobility funding directive have shown that the programmatic goals are being met. The "Erneuerbar Mobil" subprogram has been particularly successful, establishing itself as a viable construct within the electromobility funding landscape for addressing long-term research and innovation topics of societal and economic relevance (BMF, 2023).

These measures are part of the Climate and Transformation Fund of the German government and have various expiration dates, with some initiatives scheduled to end as late as June 2026. The initiatives are primarily financed through EU aid and are categorized as productivity aids (BMF, 2023).

4. Results and discussion

The following section presents the results of the analysis of the German car market, the cost analysis and allocation of subsidies and tax revenue shortfalls based on the methodology shown in section 2, as well as the incentives-induced CO_2 emissions and abatement cost reduction.

4.1. *German car market evolution*

Below, based on the identified incentives, the evolution of the German car market is analyzed to assess the effectiveness of these measures. Therefore, new registrations and the number of subsidized vehicles by the environmental bonus are analyzed.

4.1.1. *New car registrations*

In the evolving landscape of the German car market, a significant shift is evident in the composition of new vehicle registrations, driven by changing consumer preferences and regulatory incentives. Fig. 2 provides a detailed depiction of this shift, showcasing the relative shares of

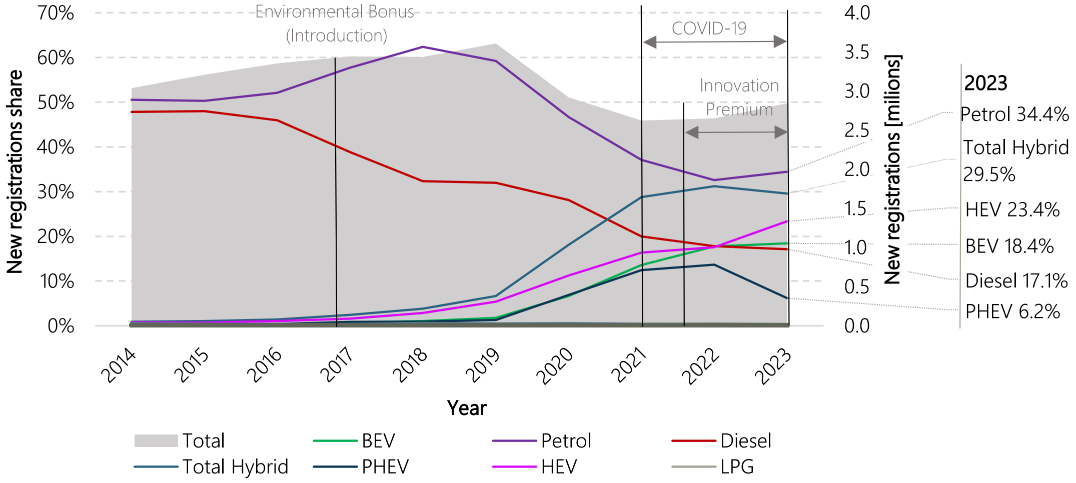

Fig. 2. New car registrations in Germany 2014–2023 by powertrain(lines: relative; area: absolut) (KBA, 2023; KBA, 2023; KBA, 2023)

new registrations across different powertrain technologies as lines and the total registrations as a grey background.

Thus, hybrids, a combination of Hybrid Electric Vehicles (HEVs) and PHEVs have gained importance. PHEVs, in particular, receive separate attention due to their incentivization under various government programs. Since the introduction of the environmental bonus in 2016, all incentivized technologies, including PHEVs and Battery Electric Vehicles (BEVs), have seen increasing shares, with a noticeable surge starting in 2019.

The period between 2015 and 2023 experienced a remarkable surge in the annual new registrations of BEVs, PHEVs, and FCEVs, rising from 55,213 new registrations in the year 2015 to a substantial 2.51 million in the year 2023 (KBA, 2023; KBA, 2023; KBA, 2023). This significant growth is predominantly attributed to the various incentives implemented by the government, successfully catalyzing the adoption of alternative powertrain vehicles.

A declining trend is observed in conventional internal combustion engine (ICE) technologies, such as diesel- and petrol-powered vehicles. Diesel has consistently declined since 2015, partly due to stricter air pollution limitations in cities (particularly concerning NO$_x$ emissions) and fears of urban diesel bans. The VW diesel-gate scandal in the year 2015 further tarnished the image of diesel-driven cars (Deutschlandfunk, 2021; Schweizer Tagblatt, 2019). Those circumstances led to a shift from diesel to petrol, which peaked in 2018 with a 62 % share in new registrations. However, since 2018, the share of petrol has steadily been replaced by hybrids and BEVs.

The introduction of stricter CO$_2$ fleet limits for original equipment manufacturers (OEMs) has necessitated the adoption of alternative powertrains, initially leading to an increased market share of HEVs. The reform of the environmental bonus in the year 2019 catalyzed the market entry of both BEVs and PHEVs, further supported by tax benefits for these vehicle types. Interestingly, CNG and LPG vehicles no longer play a significant role in new registrations (European Commission, 2023).

The shares of PHEV and BEV have been rising simultaneously and similarly since the year 2019. The motor vehicle tax reform in 2021 based on tax assessments on CO$_2$ emissions provided an even stronger incentive to move away from ICE vehicles. However, the end of the environmental bonus for PHEVs in the year 2022 led to a decrease in their shares, as the technology remains more expensive compared to ICE vehicles. In contrast, BEVs continued their upward trajectory, reaching an 18.4 % market share of new registrations by 2023, supported by the continued environmental bonus until December 18, 2023 (BMF, 2020; Zoll, 2020)

One key observation is the noticeable decrease in the absolute number of new vehicle registrations. This trend is significantly influenced by the COVID-19 pandemic. This profound impact on consumer behavior and the broader market led to a downturn in new vehicle purchases. However, amidst these challenging economic times, introducing the innovation premium in June 2020 played a crucial role in bolstering the market. This incentive effectively counteracted the pandemic's negative impact by encouraging continued growth in the market share of electric vehicles, even during time periods of economic uncertainty. The cost of the innovation premium alone amounted to more than 2.7 Billion € between July 2020 and June 2022 (based on (German Bundestag, 2022a; German Bundestag, 2021)).

Finally, the enduring popularity of Hybrid Electric Vehicles (HEVs) is noteworthy. Despite the absence of a purchase premium for these vehicles, HEVs have remained a popular choice among consumers. This sustained interest can be attributed to their relatively lower prices compared to fully electric vehicles and favorable emissions ratings. Furthermore, HEVs offer a lower total cost of ownership (TCO) and alleviates range anxiety concerns for consumers. Further, HEVs were also attractive to manufacturers as they helped to align with CO$_2$ fleet limits.

4.1.2. Subsidized cars by environmental bonus

The left graph in Fig. 3 displays the annual new registrations of vehicles subsidized by the environmental bonus from 2015 onwards till November 2023. It reveals a significant increase in the number of subsidized vehicles, with a notable peak in the year 2022, when 820,368 vehicles were subsidized, accounting for 30.9 % of all new registrations in that year. This peak can largely be attributed to the introduction of the innovation premium, which significantly boosted the number of subsidized PHEVs and BEVs.

The right graph offers insights into the share of vehicles subsidized by the environmental bonus in new registrations for each powertrain technology. Although the environmental bonus was discontinued for PHEVs in 2023, the BAFA received 478 PHEV subsidy applications. However, there are differences in the data time stamps of application, the approval, and the payment of these subsidies, resulting in a time shift of approvals and payments. This effect leads to subsidies of PHEV even after the formal termination of this program in 2023 (BAFA, 2023; BMF, 2023).

A key observation for 2023 is the notable decline in the share of subsidized new PHEV registrations, dropping by 64 %. This decrease is primarily due to the discontinuation of the environmental bonus for PHEVs, resulting in a reduction in new PHEV registrations from 14 % in 2022 to just 6 % in 2023 of the total car market. Furthermore, the termination of the innovation premium in December 2022 resulted in a reduction in new BEV registrations. However, the subsidy share for BEV

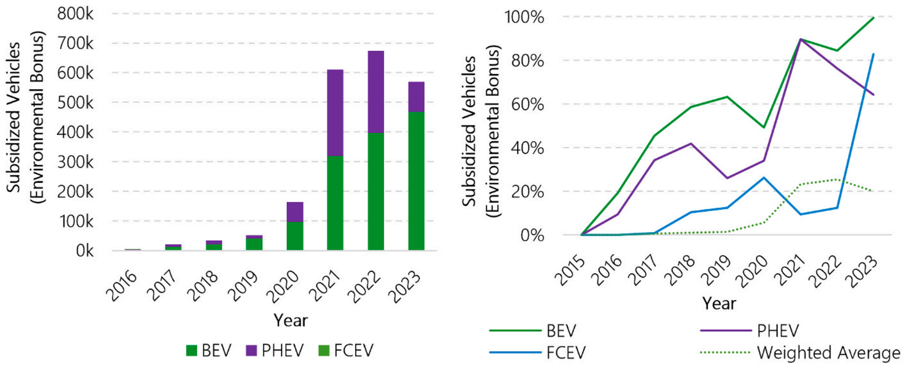

Fig. 3. New registrations of EVs subsidized by environmental bonus from 2015 to Nov 2023 (left) and share of vehicles subsidized by the environmental bonus in new registrations (right). (Bafa, 2023; Ecomento, 2016; Ecomento, 2017; Ecomento, 2018; Ecomento, 2019; Ecomento, 2020; Ecomento, 2021; Ecomento, 2022; Ecomento, 2023; Ecomento, 2023).

remained relatively high at 78 %.

Interestingly, FCEVs have not seen significant registration numbers throughout this period, indicating that they have no substantial impact within the German market.

To sum up, the environmental bonus has been a key driver in the exponential growth with a 250 % increase in subsidized vehicles, particularly between 2020 and 2021, This growth trajectory underscores the effectiveness of the environmental bonus as a policy tool in promoting the adoption of electric vehicles and shaping consumer preferences in the German automotive market.

4.2. *Total federal costs of subsidies and tax revenue shortfalls*

In the following, the costs of Germany's EV incentives between 2015 and 2023 are analyzed. This investigation is pivotal to comprehending the fiscal impact these incentives have exerted on public finances.

Fig. 4 offers a detailed overview of the costs incurred due to subsidies and funds from explicit federal incentives, alongside the tax revenue shortfalls from implicit federal incentives. The aggregate total of the expenses in supporting EV adoption during this period amounts to approximately 17.2 billion €, of which subsidies constitute approximately 14.3 billion € and tax revenue shortfalls roughly 2.9 billion €. Fig. 4 traces the evolution of explicit subsidies and funds, revealing an initially modest fiscal impact from 2015 to 2019. This period, corresponding to the 'innovators phase' in the bass diffusion model, was characterized by gradual market penetration of alternative powertrains (Ensslen et al., 2019; Fluchs, 2020). A notable increase in these costs ensued following the increase in the environmental bonus in November 2019, which significantly supported purchases of incentivized vehicles. The subsequent years, marked by the COVID-19 pandemic, witnessed a doubling of the federal share of the environmental bonus (due to "innovation premium"). This intervention led to an explosive rise in new registrations of alternative powertrains. However, the removal of subsidies for PHEVs and the restriction of the environmental bonus to private consumers in the year 2023 will lead to a decrease in government spending in the future until spending on tax losses increases.

Concurrently, the growing number of EVs necessitated augmented subsidies for charging infrastructure. This trend is projected to continue into 2024 and the following years (BMF, 2023). Further, the trajectory of implicit incentives is increasing through tax revenue shortfalls. These shortfalls have been found to correlate directly with the number of eligible vehicles in the market. Consequently, as the registrations of eligible cars increased, so did the tax revenue shortfalls, with the company-owned car tax reduction emerging as a predominant driver of these costs. Post the expiration of each incentive's registration period, a stabilization in associated costs is expected to manifest distinctly from 2025 to 2030. Between 2015 and 2019, these costs were primarily driven by subsidies (mainly "environmental bonus"). As the shares of electric vehicles rose, the tax revenue shortfalls began to impose a more significant burden on the total costs. Meanwhile, the subsidies, particularly those from the environmental bonus, were scaled back and refined to target specific vehicle types. In the forthcoming years, tax revenue shortfalls are projected to dominate the cost spectrum, while subsidies for charging infrastructure are expected to persist until such infrastructure becomes economically viable.

4.3. *Specific federal costs per eligible vehicle*

In the assessment of the fiscal impacts of EV incentives in Germany, a nuanced understanding emerges when dissecting the allocation of these

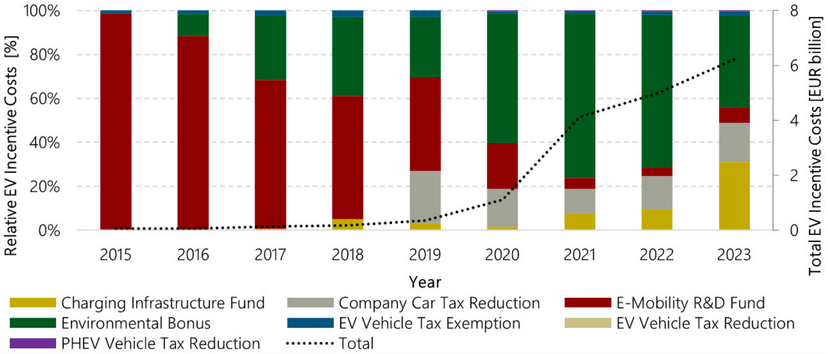

Fig. 4. Relative and absolute costs of federal subsidies and tax revenue shortfalls between 2015 and 2023 in EUR billion (relative and absolute) (BMF, 2015; BMF, 2017; BMF, 2019; BMF, 2021a; BMF, 2023).

incentives across various user cases. This understanding is crystallized in Table 4 and Fig. 5 showing the distribution of federal incentive costs. Table 4 presents the incentives, their applicability to user groups, and their derived allocation key. Fig. 5 categorizes these costs within a 2x2 matrix, considering the most pertinent user groups – company-owned cars (CC) and private-owned cars (PC) – and the principal powertrain technologies BEV and PHEV. This classification is pivotal for delineating the diverse impacts of EV incentives on the federal budget and for appreciating the specificity of cost allocation among different user groups and vehicle types.

A detailed analysis of Table 4 reveals the selective applicability of each incentive, contingent on the powertrain technology and user group. This differential applicability necessitates a bespoke allocation key for each incentive, ensuring an accurate reflection of the financial burden on the federal budget. The comprehensive allocation of charging infrastructure costs echoes this tailored approach. The underutilization of the existing charging infrastructure points to potential future cost reductions (although immediate allocations suggest otherwise (BDEW, 2023)).

Fig. 5 extends this analysis by presenting a 2x2 matrix that juxtaposes user groups against powertrain technologies, revealing the specific federal incentive costs. This figure highlights the assumption of the incentives listed in Table 4 are applicable to each case. For instance, CC PHEVs are not subsidized by the environmental bonus in 2023 anymore but still accrue benefits from tax incentives, translating to lower average costs for explicit and implicit subsidies. A striking observation is the higher subsidization of BEVs compared to PHEVs, primarily due to the tax exemption and a more substantial environmental bonus. Furthermore, company-owned cars receive more significant subsidies than private-owned cars, especially due to the company-owned car tax exemption and the resulting tax revenue shortfall for the national household. The costs are annually allocated in the year they occur.

In examining private-owned cars, the environmental bonus emerges as the principal cost driver, with charging infrastructure costs also playing a significant role. As for company-owned cars, the environmental bonus remains a major driver, albeit with a relatively smaller share compared to privately owned cars. The company-owned car tax reduction, particularly since its peak in 2019, stands out as a notable cost component. Before 2019, e-mobility R&D costs as market-enabler were predominant, shifting later to the second-largest contributor.

4.4. CO_2 emissions and abatement costs over vehicles

In the following, scenarios and assumptions are presented to calculate the CO_2 emissions of subsidized e-vehicles and assumed substituted petrol vehicles. Furthermore, the cost analysis is used to calculate the CO_2 abatement cost reduction for customers through government incentives.

4.4.1. Scenarios

In evaluating the efficiency of Germany's policy package for EV incentives, a critical metric employed is the CO_2 abatement costs. The significance of these CO_2 abatement costs lies in their utility as a benchmark for future governments contemplating similar e-mobility incentive packages. However, it is crucial to recognize that these costs are influenced by specific national contexts. For instance, Germany's status as a "new car country" with a minimal import of used cars significantly shapes its vehicular landscape. This contrasts with countries like Bulgaria or many African nations, where the import of older cars is more common (Held et al., 2021).

Table 5 establishes a framework for calculating CO_2 abatement costs across three scenarios: base, minimum, and maximum. These scenarios are differentiated by the emission factors attributed to various energy sources, critical for determining CO_2 emissions savings and abatement costs.

In this analysis, we assume an average annual transport distance of 16,200 km for alternative vehicles (KBA, 2024b) with an estimated vehicle lifetime of 17 years (BMVU, 2017) for the German car market. For emission factors related to conventional fuels like petrol and diesel, the study draws from figures provided by the (Helmholtz Gesellschaft, 2020). The base case reflects current electricity emission factors in Germany, offering a contemporary perspective (Electricity Maps, 2022). The maximum scenario envisions higher emission factors due to increased reliance on carbon-intensive energy sources, whereas the minimum scenario assumes a more optimistic shift toward lower emission factors for both electricity and hydrogen.

A key variable in this analysis is the electric mode share for PHEVs which quantifies the proportion of kilometers driven in EV mode rather than using the internal combustion engine (ICE). This assumption is grounded in data from (Plötz et al., 2022), which covers both private and corporate PHEV users. The results of the CO_2 emissions and abatement cost calculations across these scenarios, including production-related emissions, provide a holistic view of the environmental benefits and cost-effectiveness of Germany's EV incentive policies.

4.4.2. CO_2 emissions

Fig. 6 provides a depiction of annual and cumulative CO_2 emissions, focusing exclusively on operational (tailpipe) emissions and thereby excluding vehicle production emissions.

The bars in Fig. 6 and Fig. 7 represent the base case scenario for each year. Specifically, the left bar for each year delineates the CO_2 emissions attributable to a petrol substitute. This hypothetical case estimates the emissions that would have been produced if the fleet of alternative powertrain vehicles consisted of ICE petrol cars, serving as a comparative benchmark. Central to these figures is the stacked bar that shows the emissions from different alternative powertrains, namely BEVs, PHEVs, and FCEVs. The data for these emissions are derived under the assumptions outlined in Table 5, providing a detailed breakdown of emissions by powertrain type. Adjacent to these stacked bars, the right columns in each year's segment display the annual CO_2 savings achieved by adopting the alternative powertrains as opposed to the petrol substitute scenario. Moreover, the figures include variation bars, representing the total ranges for the minimum and maximum cases. These variations offer insights into the potential variability in emissions and

Table 4
Applicability of EV incentive cost allocation on different use cases.

Incentive	Allocation Key	Company-owned Car (CC)		Private-owned Car (PC)	
		CC BEV	CC PHEV	CC BEV	CC PHEV
Company Car Tax Reduction	Subsidized CC	x	x		
EV Vehicle Tax Exemption	TR BEV/FCEV	x		x	
EV Vehicle Tax Reduction	TR BEV/FCEV	(x)		(x)	
PHEV Vehicle Tax Exemption	TR PHEV		x		x
Environmental Bonus	By powertrain (BAFA data)	(01.09.2023)	(31.12.2022)	(18.12.2023)	(31.12.2022)
Charging Infrastructure Funds	TR EV	x	x	x	x
E-Mobility R&D Funds	TR EV	x	x	x	x

CC: Company-owned Cars; PC: Private-owned Cars; TR: Total Registrations; EV: Electric Vehicle (incl. BEV, PHEV, FCEV); BEV: Battery Electric Vehicle; FCEV: Fuel Cell Electric Vehicle; PHEV: Plug-in Hybrid Electric Vehicle; BAFA: Federal Office for Economic Affairs and Export Control

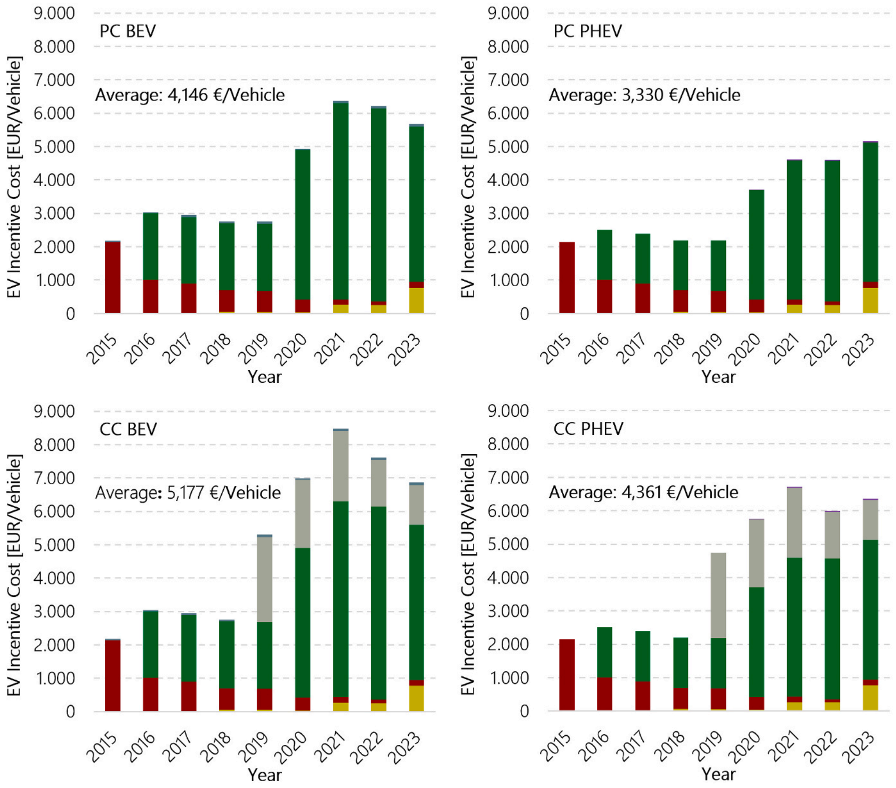

Fig. 5. Specific federal incentive costs per user group (PC & CC) and subsidized powertrain technology (BEV & PHEV). PC: Private Cars; CC: Company Cars [own calculations].

Table 5
Assumptions and Scenarios for CO_2 Abatement Cost Calculations.

Variables Operation	**Unit**	**Base**	**Max**	**Min**	**Reference**
Emissions Factor Electricity	$kgCO_2$/ kWh	0.4	0.6	0.1	(Electricity Maps, 2022)
PHEV Electricity Mode Share	–	0.2	0.2	0.2	(Plötz et al., 2022)
Emissions Factor H_2	$kgCO_2$/ kgH_2	10	16	0	(Schmidt-Achert et al., 2023)
Variable Production	**BEV**	**PHEV**	**FCEV**	**ICE (Petrol)**	
Emissions Vehicle Production [tCO_2eq]	17	13	15	10	(Umweltbundesamt, 2021)

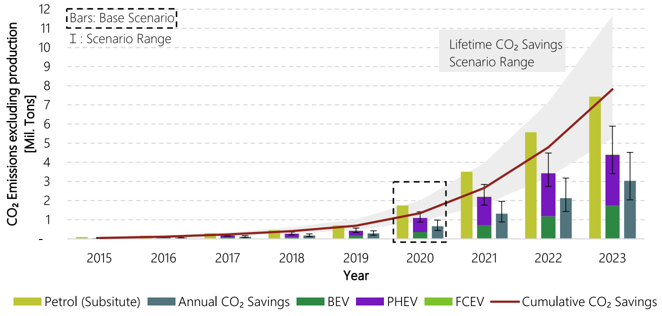

Fig. 6. Specific, annual, and cumulative CO_2 emissions from alternative powertrains, petrol substitute, and CO_2 savings excluding vehicle production emissions (based on assumptions shown in Table 5).

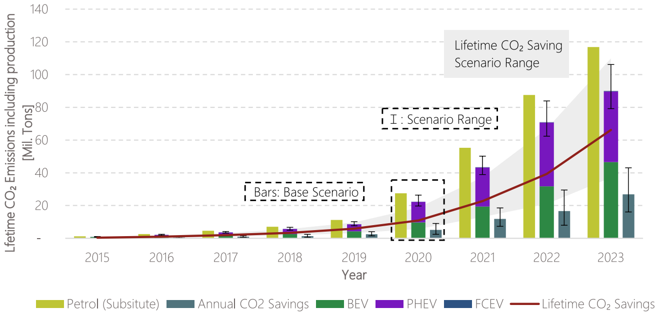

Fig. 7. Specific, annual, and cumulative CO_2 emissions from alternative powertrains, petrol substitute, and CO_2 savings, including vehicle production emissions (based on assumptions shown in Table 5).

savings under different assumptions.

A continuous line across the figures tracks the cumulative CO_2 savings over time for the base case, offering a longitudinal perspective on these vehicles' environmental impact. Accompanying this line is a background band that illustrates the spectrum of cumulative CO_2 emissions between the max and min cases.

Fig. 6 illustrates the trajectory of CO_2 savings attributed to the increasing adoption of high-efficiency alternative powertrains, particularly BEVs and PHEVs. The CO_2 savings observed each year are directly proportional to the growing presence of these alternative powertrains in the market. Notably, the annual CO_2 savings escalate as the proportion of BEVs to PHEVs increases. This trend has been particularly prominent since the reduction of subsidies for PHEVs from 2019 onward and the expected further changes in September 2023. This shift has resulted in a higher uptake of BEVs, contributing to greater CO_2 savings over the years. A significant increase in CO_2 savings is discernible following the substantial number of vehicles subsidized in 2019, leading to an exponential growth in cumulative CO_2 emissions savings up until 2023.

Fig. 7 extends the analysis of CO_2 emissions to include the significant factor of vehicle production emissions, offering a more comprehensive view of the environmental impact of EVs. This inclusion is particularly pertinent for BEVs and PHEVs, which inherently possess a higher initial CO_2 'backpack' due to the emissions involved in battery production. This necessitates these vehicles to 'catch up' during their operational phase, offsetting the higher production emissions to realize overall CO_2 savings.

Consequently, when factoring in production emissions, the annual CO_2 savings for BEVs and PHEVs are observed to be lower than what is represented in Fig. 6 only considering operational emissions. This leads to a reduction in the calculated cumulative CO_2 savings. The variation bars in Fig. 7, representing the minimum and maximum case scenarios for each year, remain consistent with those depicted in Fig. 6, as they are influenced solely by operational assumptions.

However, the increasing market share of BEVs and PHEVs adds a layer of complexity. As these vehicles become more prevalent over time, their higher CO_2 production emissions become more significant, partially diminishing the overall emission savings. This dynamic leads to a notable reduction in emission savings – 26 %/a lower cumulative savings on average compared to the cases that exclude production emissions.

The overarching analysis of CO_2 savings derived from the adoption of alternative powertrains in Germany (Fig. 6 and Fig. 7) presents an optimistic environmental outlook. Despite the incorporation of vehicle production emissions in Fig. 7 notably reducing the extent of savings compared to the assessment of operational emissions alone, the CO_2 savings remain positive in both scenarios over time.

However, these CO_2 savings are contingent upon the scope of the vehicle's operation within Germany. If the scope were to be reduced, for instance, by considering the potential export of these vehicles and/or a lower overall traveling distance within Germany, the CO_2 savings would still be realized but would no longer contribute to the annual German CO_2 balance.

In comparing the results of our study with previous research, we find both alignment and noteworthy variations in CO_2 emissions savings. For example (Sheldon et al., 2023) estimated that EVs saved approximately 1.2 million tons of CO_2 emissions annually by 2021. In comparison, our study found that, including production emissions, the CO_2 savings amounted to 0.96 million tons, while excluding production emissions (i. e., focusing solely on tailpipe emissions), the savings reached 1.31 million tons.

In a more recent study, the (Umweltbundesamt, 2023) reported 1.8 million tons of CO_2 savings in 2022. Our study found slightly lower emissions savings when production-related emissions were considered, with 1.56 million tons of CO_2 saved. However, when excluding production emissions, our results exceeded those findings, with a total of 2.1 million tons of CO_2 saved.

4.4.3. CO_2 abatement costs

Fig. 8 succinctly conveys the CO_2 abatement costs arising from federal incentives for alternative powertrains. Using stacked columns, these costs are depicted based on the base case assumptions from Table 5. A grey band within the graphics captures the range of potential outcomes under the minimum and maximum cases, providing a visual spectrum of annual CO_2 abatement costs. The following graphics differ in the exclusion and inclusion of production emissions for the vehicles.

Fig. 8 showcases the CO_2 abatement costs, excluding production emissions, drawing from the operational emissions data presented in Fig. 8. In this depiction, the average CO_2 abatement cost for the base scenario is calculated at around 1,658 €/t of CO_2. For the scenarios with varied assumptions, the average costs fluctuate, reaching up to 3,135 €/t in the maximum scenario and dropping to 915 €/t in the minimum scenario (averages of upper and lower grey band boundaries).

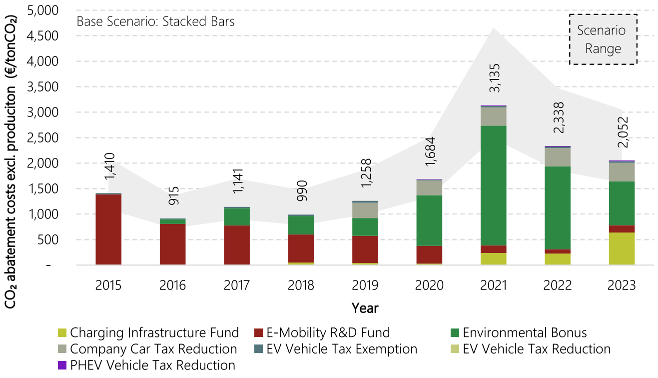

Fig. 8. CO_2 abatement costs per Vehicle, excluding production emissions.

An analysis of the period between 2015 and 2019 highlights that the e-mobility R&D fund initially played a pivotal role in driving federal costs (see also Fig. 4). Over time, however, the share of this fund in the overall costs has gradually decreased. A significant shift occurs in the year 2019 with the increase in company-owned car tax reduction correlating with the rising number of eligible registered vehicles. In the year 2020, the environmental bonus emerged as the primary cost driver, a change attributed to an upsurge in vehicle registrations. The peak abatement cost is observed in the year 2021, reaching 3,135 €/t of CO_2, predominantly due to the innovation premium introduced within the environmental bonus. As the share of electric vehicles (EVs) continues to rise, the costs associated with charging infrastructure subsidies also grow linearly.

Fig. 9 presents the analysis of CO_2 abatement costs, including vehicle production emissions, extending the insights derived from Fig. 7. This figure offers a broader perspective on the broader environmental costs of EV adoption, considering the emissions from the production phase of these vehicles. Here, the average CO_2 abatement cost for the base case is calculated at 2,254€/t of CO_2, with a significant variation observed across different scenarios: as high as 4,298 €/t in the maximum case and as low as 1,235 €/t in the minimum case for the average costs (averages of upper and lower grey band boundaries).

From 2015 to 2019, like the trends observed in Fig. 4, the e-mobility R&D fund initially dominates as the main cost driver. However, the proportion of this fund in the total costs gradually diminishes over time. A notable shift occurred in 2019, when company-owned car tax reduction became a significant factor due to the increasing number of eligible company cars, a trend that continues to rise until 2023. In the year 2020, the environmental bonus takes over as the primary cost driver, propelled by a surge in vehicle registrations. This shift is particularly prominent in the year 2021, where the peak abatement cost reaches 4,298 €/t of CO_2, largely due to the innovation premium included in the environmental bonus.

Parallel to the increasing market share of electric vehicles, the

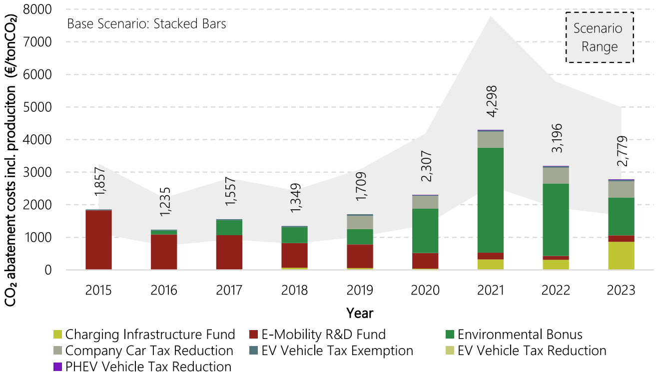

Fig. 9. CO_2 abatement costs per Vehicle, including production emissions.

subsidies allocated for charging infrastructure exhibit a linear growth, reflecting the expanding need for EV charging facilities. It is important to mention that these CO_2 abatement costs are high at introducing new technologies that require subsidies and will decline over time.

In comparison to the study by (Sheldon et al., 2023), which calculated CO_2 abatement costs ranging from 734 to 1,600 €/ton CO_2 across 11 European countries in 2017, with an average of 202 €/ton CO_2 for Germany, several key differences in methodology arise. Sheldon et al. only considered purchase premium subsidies, such as the environmental bonus, while excluding other direct subsidies and tax revenue shortfalls. In contrast, our study, which focuses on the environmental bonus allocated in Germany, estimates CO_2 abatement costs at 457 €/ton CO_2 for 2017. This higher cost is primarily due to differences in the cost allocation approach, particularly in accounting for avoided emissions or emission savings.

If we consider a vehicle lifetime of 250,000 km and assume that the vehicle remains in Germany for its entire lifetime, contributing fully to the country's GHG balance, the CO2 abatement cost excluding production would average 363 €/ton CO_2, with a range of 124 to 615 €/ton CO_2. When including production emissions, the average cost drops to 165 €/ton CO_2, ranging from 64 to 308 €/ton CO_2. However, this approach does not account for future tax revenue shortfalls from the fleet, which would likely increase the actual abatement costs. Therefore, these values should be interpreted as indicative, providing an order of magnitude rather than precise estimates, as more comprehensive data would refine these calculations.

Limitations and further aspects

In the context of assessing the CO_2 abatement costs associated with EV incentives from a federal perspective, a crucial aspect of this study involves a qualitative assessment of the known limitations. This evaluation, detailed in The qualitative assessment presented in Table 6 is based on expert opinions and key mathematical formulas used in calculating CO2 abatement costs, particularly those accounting for emissions, energy source variability, and production-related factors. The combination of expert judgment and precise mathematical modeling ensures that the assessment reflects both theoretical rigor and practical insights into the limitations and impacts of EV incentives.

Table 6

Qualitative impacts of out-of-scope limitations of this study on CO_2 abatement costs.

Limitation	Effect
	Decreasing CO_2 abatement costs:
Higher average sale prices of EVs compared to similar ICE	Increased VAT tax revenue
Increased electricity demand for charging	Increased energy tax revenue
Renewable energy in EV production	Decreasing production emissions
Low average usage of public chargers in Q1 2023 (11.6 %) (BDEW, 2023)	Indicates that todaýs infrastructure is overbuilt for market ramp-up purposes. Increases todaýs specific costs per vehicle, higher usage of existing infrastructure reduces costs
Scaling effects of charging infrastructure deployment	Reduction of cost resulting in reduced subsidies needed for business bases
GHG Quota certificate market	Annual Income for EV Owners, which creates federal tax income
Full allocation of R&D Funds and Infrastructure costs	Underutilization of installed Infrastructure - higher capacity factors will reduce cost share.R&D also benefited other sectors and modes of transport
	Increasing CO_2 abatement costs
Less oil-derived products consumption	Energy tax shortfall decrease
Income Tax Benefit for private chargers	Income tax revenue shortfall
Average consumption data	Consumers mainly bought cars with higher average consumption (PHEV/BEV) during the period
Multiple credits for electricity use in GHG certificate market	Reduce federal income from CO_2 market

EV: Electric Vehicle; ICE: Internal Combustion Engine; VAT: Value Added Tax; GHG: Greenhouse Gases.

Table 6, delves into the impact these limitations have on the cost-effectiveness and overall efficiency of the EV incentives under investigation. The table serves as a critical tool for understanding the constraints and challenges inherent in such policy assessments, offering insights into the areas where assumptions and external factors might influence the results. This qualitative assessment is essential for a comprehensive understanding of the study's findings, ensuring a balanced and realistic interpretation of the data and its implications in the broader context of environmental policy and sustainable transportation initiatives.

The qualitative assessment presented in Table 6is based on expert opinions and key mathematical formulas used in calculating CO_2 abatement costs, particularly those accounting for emissions, energy source variability, and production-related factors. The combination of expert judgment and precise mathematical modeling ensures that the assessment reflects both theoretical rigor and practical insights into the limitations and impacts of EV incentives.

Another limitation of this study is the focus on macroeconomic and environmental impacts, which excludes an analysis of potential social and regional disparities associated with EV incentives. For instance, the purchase premium incentive inherently favors individuals who can afford new or nearly new vehicles, which may exacerbate social imbalances. Lower-income households, who are more likely to rely on older used cars, are often excluded from benefiting directly from these subsidies. This highlights a disparity in access to EV incentives, as higher- and middle-income individuals are more likely to purchase new cars or benefit from company car programs. It is noteworthy that company cars account for approximately 67.5 % (Statista, 2024) of new vehicle registrations in Germany, compared to approximately 32.5 % (Statista, 2024) by private buyers, further amplifying this imbalance.

Additionally, regional disparities between rural and urban areas further complicate the equitable distribution of EV incentives. Urban areas, with greater infrastructure density and charging station availability, are better positioned to benefit from these policies, while rural areas often face limited access to the necessary infrastructure. These regional differences may lead to uneven adoption rates and exacerbate the urban–rural divide in the transition to electric mobility.

5. Conclusion

This study delves into the impact of Germany's EV incentive package on the automotive market, highlighting its role in influencing consumer choices and promoting technology adoption. Despite its significant effects, evaluating the package's effectiveness and efficiency reveals complexities.

Our methodology included identifying EV incentives, extensive data collection, and assessing the federal costs for EV market expansion in Germany. We adapted micro-level techno-economic assessment methods for macroeconomic analysis, focusing on cost allocation and CO_2 abatement costs. This streamlined approach aimed to provide a clear understanding of the incentive package's broader economic and environmental implications.

In assessing effectiveness, the study analyzed new registrations and vehicles subsidized by the environmental bonus. The implemented incentives, especially the environmental bonus, significantly accelerated EV market entry, demonstrated by a 250 % increase in subsidized vehicles from 2020 to 2021. Additionally, the innovation premium's introduction during the pandemic further boosted EV sales, proving its effectiveness in challenging times.

By 2023, BEVs accounted for 18.3 % of new registrations, while PHEVs reached their peak at 14 % in 2022. FCEVs, however, remained marginal in their market impact. Notably, 30.9 % of new registrations in 2022 benefited from the environmental bonus, affirming its critical role in promoting EV adoption.

Efficiency evaluation of the incentive package reveals significant fiscal commitments and nuanced outcomes: The fiscal analysis shows that between 2015 and 2023, the combined costs of tax revenue shortfalls and subsidies for EVs reached approximately EUR 17 billion, with costs peaking in 2023 at EUR 6.2 billion. The concept of economies of scale is evident, as seen in other sectors, where increased production volumes lead to decreased unit costs, enhancing the accessibility of technologies.

To analyze costs effectively, four cases were established based on use case and powertrain, facilitating the allocation of subsidies and tax shortfalls. Average subsidy values per vehicle across powertrains (BEV, PHEV) and use cases (private or company cars) were calculated: PC BEV at EUR 4,146, PC PHEV at EUR 3,330, CC BEV at EUR 5,177, and CC PHEV at EUR 4,361.

Concerning CO_2 emissions, two scenarios were considered, one excluding and one including vehicle production emissions. The base scenario excluding production emissions resulted in savings of 3 million tons of CO_2 between 2015 and 2023 with subsidized vehicles, while including production emissions saw savings of 2.2 million tons CO_2 when compared to average substituted petrol cars.

The CO_2 abatement cost analysis illustrates the reduction of consumer costs induced by federal incentives. The federal CO_2 abatement cost, excluding production emissions, averaged 1,658 EUR/tonCO_2, with a range of 915 to 3,135 EUR/tonCO_2 from 2015 to 2023. Including production emissions, the average rose to 2,254 EUR/tonCO_2, with a range between 1,235 and 4,398 EUR/tonCO_2 for the base scenario.

Assuming a vehicle lifetime of 250,000 km within Germany, the CO_2 abatement cost averages 363 EUR/tonCO_2 excluding production emissions (ranges 124–615) and 165 EUR/tonCO_2 when production emissions are included (ranges 64–308). These estimates provide an indicative magnitude but exclude future tax revenue shortfalls, suggesting actual costs could be higher with improved data availability.

EV incentives played a crucial role in mobilizing private capital, offsetting the higher average purchase prices, particularly through the environmental bonus. Companies, significant contributors to new registrations, were effectively incentivized. This shift in purchase decisions provided more robust financing for car manufacturers for EV research and development, influencing OEMs' equity and the allocation of federal subsidies.

Consequently, despite its initial high costs, the incentive package has proven to be an efficient and effective strategy for transforming the car sector in Germany. This transformation is not only reflected in the substantial CO_2 savings achieved but also in the stimulated growth of the EV market, showcasing the package's comprehensive impact on promoting sustainable mobility.

The German experience with EV incentives offers crucial insights for policy design, highlighting the delicate balance between fostering technological innovation and managing societal impacts. While the incentives have undeniably accelerated EV adoption and contributed to environmental goals, their long-term effectiveness in creating equitable and sustainable transportation systems will depend on addressing these broader societal and market dynamics. As Germany and other nations continue to navigate the transition to sustainable mobility, these lessons will be invaluable in shaping future policies that are not only environmentally sound but also socially inclusive.

However, the landscape of EV incentives in Germany encountered pivotal changes in 2023. Decisions by the German Supreme Court, alongside adjustments introduced through the Climate Transformation Fund, which led to a EUR 60 billion budget shortfall, prompted a reevaluation of existing policies. These developments have particularly impacted the future of the Environmental Bonus, with its discontinuation slated for 2024, alongside shifts in the focus of battery cell research and development efforts (ZDF, 2023; Handelsblatt, 2024; Focus, 2024). These changes signify a critical juncture in Germany's policy strategy, highlighting the need to balance environmental ambitions with fiscal realities. During the early adopter phase from 2024, future research should focus on developing the acceptance of EVs in Germany after the environmental bonus. Further, the methodology should be adapted to other countries' incentives to create a broader picture of successful policymaking in this field.

Future studies could broaden the scope of analysis by exploring equity, accessibility, social acceptance, and regional disparities in EV adoption. These dimensions are critical to understanding how EV policies impact different social groups and regions, ensuring the equitable distribution of benefits. For example, examining EV accessibility for lower-income households or areas with limited charging infrastructure could identify adoption barriers and inform more inclusive policies. Similarly, investigating social acceptance and public perceptions could uncover behavioral and cultural factors influencing adoption rates.

Incorporating zonal analysis could further enhance these insights by examining how EV adoption varies across regions in Germany. Factors like urbanization, income levels, infrastructure availability, and commuting patterns significantly shape policy effectiveness. For instance, urban areas may see higher adoption rates due to dense infrastructure, while rural areas with limited access face greater challenges. Such analyses would help policymakers optimize incentive programs, address disparities, and design tailored policies. By integrating these dimensions, future research could complement the macroeconomic and environmental analyses presented here, offering a more comprehensive evaluation of EV incentives.

CRediT authorship contribution statement

Michael Schulthoff: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Philipp Anstett:** Writing – review & editing, Validation, Software, Data curation. **Jelto Lange:** Writing – review & editing, Supervision, Conceptualization. **Dörthe Arend:** Writing – review & editing. **Emre Gencer:** Writing – review & editing, Supervision, Resources. **Martin Kaltschmitt:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and ChatGPT in order to check grammar and spelling and paraphrase manually written paragraphs by the authors to improve readability and scientific language use. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

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Submission declaration

The authors declare, that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Data availability

The used data is publicly available but not published except of the micro data of the KBA, which is only accessible behind a non-disclosure agreement (NDA). Some of the data must be requested at the ministries. Publicly available data and pre-processed data from the KBA microdata set can by provided by the corresponding author.

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