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Total Cost of Ownership and External Cost Assessment of Commercially Available Vehicles in Germany

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Abstract

This study aims to provide a comprehensive and realistic evaluation of consumer and external costs associated with commercially available passenger cars. The central research question is: How do Total Cost of Ownership (TCO) and external costs differ between conventional vehicles, Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs) across various vehicle segments? The methodological approach includes the selection of 55 commonly registered vehicle variants in Germany and the calculation of TCO and external costs over a 16-year vehicle lifetime. TCO components include purchase price, governmental subsidies, remaining value, fuel or energy expenses, maintenance, insurance and taxes. External costs incorporate emissions, land use and the societal costs from purchase bonuses. Apart from the large quantity of considered vehicles and the depth of investigation, this study's main contribution is the consideration of tax revenue as a negative external cost. The results show that BEVs consistently exhibit the lowest TCO and external cost across all segments. For example, a BEV in the E segment has 26% lower TCO and 14,300 € lower external cost than an equivalent diesel vehicle. FCEVs show competitive results in both TCO and external costs, though limited by market availability. While higher in TCO, vehicles in higher segments generally lead to lower external cost due to higher tax revenue. The findings support the economic and ecological advantages of BEVs, which should therefore be primarily considered by consumers and policy-makers.

Keywords: external costs; germany; life cycle assessment; passenger cars; tax revenue; total cost of ownership

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1. Introduction

The global climate change represents one of the most pressing challenges of our time, demanding immediate and comprehensive action to reduce Greenhouse Gas (GHG) emissions and mitigate the adverse effects of global warming. At the forefront of this environmental crisis stands the issue of CO_2 emissions, substantially originating from the transportation sector, which, at 16.6% [1], is the fourth [2] largest source of man-made CO_2 emissions globally. Passenger transportation in the form of cars, motorcycles, cabs and buses accounts for 45.1% [3] of transportation emissions, 7.5 billion tons of CO_2 equivalent in total [3]. To combat GHG emissions in the transportation sector, the adoption of Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) has emerged as a promising strategy, presenting a potential shift towards more sustainable mobility

solutions [4]. In addition to CO_2 emissions, particularly fossil Internal Combustion Engine Vehicles (ICEVs) are responsible for other negative externalities, such as air and noise pollution in residential areas and depletion of finite resources [5]. However, the widespread adoption of pure electric and hydrogen-based vehicles faces different hurdles, notably their higher upfront cost, charging time and limited driving range compared to conventional ICEVs [6–8].

Since purchase costs remain the most apparent distinction between the vehicle concepts from a consumers point of view, this paper posits that evaluating the Total Cost of Ownership (TCO) and accounting for external costs is imperative for a more comprehensive analysis of the economic and environmental impact of passenger cars.

The purchase price of a vehicle often overshadows other considerations when consumers make decisions about their choice of transportation. However, it is important to emphasize that the TCO, encompassing not only the initial purchase price but also operating costs over the vehicle's lifetime, provides a more comprehensive view of the economic feasibility of BEVs, FCEVs and ICEVs. Among others, maintenance, fuel, insurance, taxes, depreciation, or recycling are essential components in the analysis of TCO. An accurate assessment of the TCO could provide insights into whether the overall expenses during the lifespan of different vehicle concepts differ significantly, and whether there is a single concept superior to the others.

Furthermore, when evaluating the environmental impact of vehicles, it is crucial to consider external costs—those costs that are borne by society at large rather than the vehicle owner [5]. These external costs include air pollution, noise pollution, road congestion, and the healthcare costs associated with diseases linked to vehicle emissions. The consideration of external costs, both for sustainable vehicle concepts and conventional ICEVs, is integral to making informed policy decisions and ensuring that the true societal and environmental costs of transportation are accounted for.

Within this work, a comprehensive analysis of the TCO and external costs associated with a selection of currently available passenger cars is provided. By investigating these dimensions, we seek to contribute valuable insights that can guide consumers, policymakers, and the automotive industry towards making informed decisions that prioritize sustainability, economic efficiency, and environmental well-being in the face of the global climate change.

The following Section 2 describes the basics of TCO and external costs and discusses existing literature. Section 3 describes the methodology used to determine the corresponding costs. Section 4 presents the results, and is followed by a discussion of the results and methodology in Section 5.

2. Fundamentals of TCO and External Cost

This section describes the fundamentals and existing research concerning TCO and external cost calculations. It explains how both calculations are carried out and points out findings published in other work.

2.1. Total Cost of Ownership

TCO refers to a cost management method that deals with the total amount of money spent by the owner of a product over its entire life cycle [9]. It includes all costs that must be settled from purchase to disposition. Within the scope of this paper, the product is a passenger car, and the owner of the product is the owner of the vehicle.

2.1.1. Fundamentals

When looking at the TCO of a product, it is merely a closer look at how the value of the product develops over time, taking into account other influencing factors and costs incurred during the life cycle.

Both the creation and the calculation of the individual cost components of a TCO management method are not standardized, nor are there regulations or a fixed theoretical opinion. Accordingly, TCO is to be understood as a best practice approach.

Direct costs include all expenses that can be directly allocated to the IT department, such as depreciation for hardware and software, leasing fees and wages. Indirect costs include losses in value due to inefficiency-inhibiting processes, such as self-support by end users and downtime. This is followed by the introduction of cost factors such as IT infrastructure (hardware and software), maintenance contracts, management, support services, activities related to the use of IT infrastructure, periods of unavailability and disaster prevention. Finally, a classification into cost categories like general user costs, costs for Enterprise Resource Planning (ERP) systems, network operating costs, migration costs and costs for legacy systems.

Due to its generic nature, this approach can be applied to most products and services. Comparable and competing cost accounting methods are described hereinafter.

Life cycle costing, also known as cradle-to-cradle, is a similar approach, but it only looks at acquisition costs, operating costs, and disposal costs, i.e., without environmental costs or costs incurred by third parties or the social environment.

An investment appraisal examines the economic viability of an investment. Either the absolute advantageousness, a positive contribution to the company result, or the relative advantageousness, better than an alternative solution, is analyzed. These calculations are based on forecast data, which involves uncertainties. Risks can be visualized and evaluated using scenario analyses, and higher risks should be compensated for by higher expected results [10]. A distinction can be made between the following forms of investment. Static investment methods utilize performance indicators from cost and revenue calculations in order to minimize the effort required for data collection and calculations. Average values are used instead of individual data, which only provides approximate values for varying payment structures. The method is now outdated and was only used because of the low computational effort and for the sake of simplicity. Dynamic investment methods, which are more computationally intensive, analyze several periods with regard to profitability. Here, the present value of the income over several periods is compared with the investment expenditure. This method requires complex data collection, as cash flows are weighted over time by means of compounding or discounting. An investment is considered profitable if the present value of the income exceeds the investment expenditure [11]. The dynamic (financial mathematical) investment calculation is based on the payment series of an investment. Recognizing interest and compound interest, payment series can be summarized in an amount at the beginning t_0 of the payment series (present value) or at its end t_n (terminal value) or at another point in time [12].

The Visualization of Financial Implications (VoFI) differs from the traditional methods mainly in that the various conditions for borrowing and investing funds are taken into account, i.e., different market interest rates can be taken into account. This means that not only the directly attributable payments of an investment (the so-called original payments), but also the payments attributable to financial dispositions with regard to the investment, such as financing and tax payments (the so-called derivative payments), are explicitly taken into account. The VoFI method is therefore a well-suited instrument for visualizing and taking into account the complex economic and financial effects of long-term investment decisions [13].

Costs can be considered from the supplier's point of view or from the buyer's point of view [9]. From the supplier's perspective, the focus lies on how much it costs to produce goods or services and deliver them to a customer. This includes elements such as labor, packaging, raw materials, overhead, transport, post-sale costs, etc. From the buyer's point of view, TCO is the sum of all expenses that he or she will incur over the lifetime of the product. The buyer should have a process in place to calculate the true cost of a particular purchase, taking into account not only the price but also the more nuanced factors such as the costs of repairs, maintenance, fuel, and depreciation [9].

This paper focusses on TCO from the buyer's perspective. To perform a TCO assessment, it is essential to be familiar with the product to be evaluated, and one must be aware of the specific product cycle and its associated components. This allows for the identification of known cost drivers or hidden costs before an investment decision is made. The publication of [14] suggests that a generic TCO model is not appropriate. However, the authors suggest that a TCO model based on a core set of cost drivers and an auxiliary set of cost drivers is superior, as it was therefore implemented in this paper.

2.1.2. Existing Research

BEVs are often believed to be way more expensive than their ICEV counterparts, mainly because of their high initial costs for purchasing the vehicle. Examples of this belief are wide-spread in the media [15,16] and scientific papers. In contrast, the operational costs are mostly believed to behave in the opposite way. Since the availability of electric vehicles only rose around 2013, when the first generations of the Tesla Model S, BMW i3 and Nissan Leaf began to attain a small market share, earlier TCO analyses are now outdated. This is mainly due to the significant improvements in automotive engineering and reduction in purchase prices. Therefore, only existing comparative research more recent than ten years, i.e., starting from 2015, is considered to be relevant for this literature review. An overview of the relevant existing vehicle TCO studies is given in Table 1.

Table 1. Overview of existing studies assessing the TCO of passenger vehicles.

Study	Year	Drive Trains	Vehicle Segments	Region	One-Time Costs	Fuel Costs	Running Costs	Runtime
[17]	2015	ICEV, (P)HEV, BEV	A, B, C, D, J	Germany	purchase, resale	combined	combined	–
[18]	2016	ICEV, (P)HEV, BEV, FCEV	A, B, C, D, C-SUV, M	Germany	purchase, subsidies	separate	separate	12 years
[19]	2016	ICEV, HEV, BEV	B/C	Sweden	purchase, subsidies, resale	combined	separate	3 years
[20]	2017	ICEV, HEV, BEV	B	USA	purchase	separate, incl. CO_2	separate	15 years
[21]	2018	ICEV, (P)HEV, BEV	B/C	Japan, USA, UK	purchase, subsidies	separate	separate	3 years
[22]	2019	ICEV, BEV	M	UK	purchase excl. tax, resale & subsidies	separate	separate	8 years
[23]	2020	ICEV, BEV	2- & 3-wh., A, B	India	purchase, resale	combined	combined	10 years
[24]	2020	ICEV, BEV, FCEV	N	EU	purchase excl. tax, resale, subsidies	separate	separate	10 years
[25]	2021	ICEV, (P)HEV, BEV, FCEV	A, B, C, D, SUV	USA	purchase, resale, financing	separate	separate	10 years
[26]	2021	ICEV, BEV	modeled	USA	modeled	combined	combined	3–13 years
[27]	2022	ICEV, HEV, PHEV, BEV	modeled	Thailand	combined	combined	combined	10 years
[28]	2023	ICEV, HEV, PHEV, BEV	C, 2-wh.	Tanzania	purchase, resale	separate	separate	5–10 years
[29]	2024	ICEV, BEV	D	USA	purchase, subsidies	separate	separate	1 year
[30]	2024	ICEV, HEV, BEV	C, D, C-SUV, D-SUV, Pickup Truck	USA	purchase, subsidies, fees, add. equipment	separate	separate	25 years
[31]	2025	ICEV, BEV	A, B, M	ASEAN	purchase	separate	insurance, maintenance	15 years
[32]	2025	ICEV, PHEV, BEV	modeled	China	purchase, tax, subsidies	combined	combined	5 years

Over the last decade, TCO studies have expanded across multiple regions, vehicle segments and drivetrain technologies. However, they differ considerably in scope, methodology and data quality, which limits cross-study comparability.

A first major limitation is the use of short or unrealistic time horizons. Several works like [19,21,22] apply ownership periods of only 3 to 8 years, which overemphasizes early depreciation while failing to represent long-term operating cost differences, particularly relevant for BEVs, whose lifetime energy and maintenance savings accumulate over time. Even longer-horizon studies like [20] often rely on very small vehicle samples, limiting statistical robustness. Publications like [17,29] only account for a single year of utilization or do not state a time horizon and therefore neglect purchase cost and depreciation altogether. Finally, ref. [30] consider the vehicles to be used for 25 years, which is unusually long.

Second, many studies depend on modeled or hypothetical vehicle data instead of real configurations [25–27,32]. Because battery costs, consumption values and equipment options change rapidly, such assumptions quickly become outdated and reduce real-world applicability. The issue is compounded by the common absence of harmonized equipment levels, making cross-drivetrain comparisons inconsistent.

Third, existing research frequently suffers from incomplete cost modeling. Insurance, taxes, maintenance, purchase bonuses or region-specific energy prices are sometimes excluded or simplified [22,23,28]. As a result, TCO outcomes vary more due to methodological omissions than due to intrinsic drivetrain differences.

A fourth trend is limited drivetrain or vehicle segment coverage. Some studies like [21] exclude diesel ICEVs, which are still relevant in Europe, whereas others neglect FCEVs due to low market penetration. In [18], for instance, the results especially for alternative fuel vehicles are based on assumptions rather than real vehicle data. Publications like [20,22,24,29] only consider a single vehicle segment while [31] only accounts for a single ICEV and BEV per country. Consequently, comparisons across the full spectrum of commercially available vehicles and technologies remain scarce.

Overall, the literature reveals a clear pattern: TCO analyses increasingly recognize BEVs as cost-competitive or advantageous, but results depend heavily on assumptions regarding usage duration, vehicle selection, subsidies and energy prices. Yet, no existing study provides a large-scale, real-vehicle, harmonized TCO comparison covering all major German vehicle segments and including ICEVs, BEVs and FCEVs simultaneously.

2.2. External Cost

Apart from the direct costs that incur for a consumer, every purchase as well as the use of a vehicle leads to hidden costs. These are commonly referred to as external costs. This term means that although the costs need to be paid for by someone, it is not the consumer who directly pays for them. Some non-society oriented studies do not incorporate those costs [33]. However, these external costs can be directly linked to the vehicle.

The most common costs that are considered to occur from vehicle usage are congestion, accidents, barrier effects, air pollution, GHG emissions, land use and noise. These effects are well understood, and several studies already calculated these external costs for passenger vehicles [34,35].

One approach is to use pigouvian kilometer taxes for road vehicles. In doing so, a part of the external cost is paid by those who cause the costs. Since costs are not evenly distributed, e.g., congestion is more likely in higher urbanized regions than rural regions, a system with a region dependent tax might be a better solution [36].

All vehicles considered in the context of this work are passenger cars. As tolls are levied on cars in most EU countries regardless of emissions, these are neglected in this paper.

However, there are proposals where the kilometers tolls depend on emissions, as is common for heavy duty vehicles (lorries) [37,38]. If this is applied to cars in addition to CO_2 taxes on fuel, more external costs would be internalized.

A method to calculate the external cost is the use of the AFLEET Tool [39]. As [40] shows, the majority of Life Cycle Assessment (LCA) papers use the GREET model to calculate greenhouse gas emissions, air pollutant emissions and water consumption.

The European Union (EU)'s handbook on calculating the external cost of transportation [34] investigates a variety of transport systems for several use cases in the countries of the EU. In the case of passenger cars, unspecified petrol and diesel vehicles were examined. The handbook focuses mainly on the differences between road vehicles and other forms of transport, including freight transport. Mainly the external cost through environmental destruction, loss of productivity through congestion and health cost caused by accidents were investigated. Social benefits such as tax revenue were neglected.

As in the previous studies, tax revenue was not considered in [35]. The investigation only considers air pollution, climate effects, noise emissions, land use, congestion, accidents, barrier effects and health benefits from forms of transportation with relevant physical activity. In contrast to [34], the external costs caused by accidents and congestion are given at around 8500 € and 12,300 € per vehicle, respectively. These values can be calculated with the assumption that a vehicle carries on average 1.4 persons and travels 240,000 km over its full life cycle.

2.3. Research Incentive

Currently, there is no research article available that provides a thorough investigation of real vehicles' TCO as well as their external cost over a full vehicle lifetime. Relevant publications focus either on solely the TCO of a small group of vehicles or on external costs in the context of a wide variety of transportation options such as bicycles, motorbikes, trains etc.

In Germany, passenger cars are an important type of personal transportation. Unfortunately, due to the large selection of available vehicles, finding the right choice is difficult for most consumers. Therefore, the upfront cost of purchasing a vehicle is often used to distinguish between vehicle segments and types of powertrains. The TCO is often neglected, although evaluating total costs rather than only the initial purchase price provides a more robust basis for vehicle selection. This paper contributes a TCO assessment of all relevant passenger vehicle segments and fuel types, which can simplify the selection process for consumers. It differs from previous publications due to its large selection of vehicles as well as the depth of investigation for each vehicle.

Within the context of society, external cost is more important than TCO, since the choice of a vehicle is made by an individual but the external cost affects the whole society. Unlike other publications on external cost of transportation, this paper does not aim to compare different types of transport. In general, a consumer, who is searching for a passenger car is unlikely to buy, for instance, a bicycle instead. Hence, a comparison of external cost between a large variety of vehicle segments and powertrains is yet to be published. Finally, publications about external costs only focus on negative effects on the society. However, due to financial redistribution, tax revenue from individual spending has a positive societal impact. This effect has not been investigated so far. These gaps shall be closed by this paper.

3. Methodology

This section presents an overview of the methodology used to analyse costs of commercially available passenger cars. It is divided into TCO and external cost calculations

and describes the assumptions made in preparation to the data acquisition process and the calculation formulas.

3.1. General Assumptions

Vehicle cost calculations are sensitive to the general assumptions made for data acquisition. Depending on the vehicle's usage, total lifetime, vehicle class, etc., significant deviations in the further calculations are possible.

The market share of BEVs is rapidly increasing in Germany for several years [41]. Additionally, many battery cell and vehicle manufacturers are planning to start production in Germany as the local government strongly subsidizes the industry. Since it is easy to accumulate all data that is necessary to perform the calculations within this paper, Germany, and therefore German law, is chosen as the location for all tax, insurance and purchase grant related calculations.

To ensure a good market overview while keeping the workload low for data acquisition, a preliminary selection of vehicles that are considered within this paper has to be made. Therefore, all commercially available passenger cars that currently can be purchased new are initially sorted into a vehicle segment as defined by [42]. Due to the lack of a fine division of the Sports Utility Vehicle (SUV) segment, the vehicles from the J segment are re-classified into new SUV segments. The vehicles are then classified by their energy source or fuel type. Since gasoline and diesel powered vehicles are still high in demand and BEVs are rapidly gaining market share, these vehicles are taken into account. ICEVs with alternative fuels like Liquefied Petroleum Gas or Compressed Natural Gas are losing market share and thus are not included into this study [43]. Additionally, there are hardly any vehicles of these types available for purchase, which would defeat the purpose of this paper. Plug-in Hybrid Electric Vehicles (PHEVs) have a significant market share in Germany, since there were purchase grants as well as tax benefits especially for company cars in the last years. However, due to the possibility of using two different energy sources, electricity and gasoline or diesel, it is hard to find a realistic ratio in which the different fuel types are generally used. Although a standard consumption for PHEVs is given by the Worldwide Harmonised Light-Duty Vehicles Test Procedure (WLTP), studies like [44] suggest that these values are unrealistic since the vehicles are used with fossil fuels more often than intended. This finding is supported by official data given by the European Environment Agency [45], which shows, that while all vehicles consume more fuel in real-driving cycles compared to the WLTP, the deviation is largest for PHEVs. For these reasons, PHEVs are excluded from investigation in this paper. FCEVs are slowly gaining attention in Germany and the rest of the world. Although there are only two models currently available in Germany, the inclusion of these vehicles into the calculations shall show the current status of hydrogen mobility.

For each vehicle segment, the best-selling vehicle of each fuel type is chosen as reference. This best-selling vehicle was determined from the registration statistics provided by the German Federal Motor Transport Authority [43]. Additionally, all similar vehicles from the same manufacturer, but with different fuel types, are also taken into consideration. Starting from there, optional extras for each vehicle are added if possible, so the equipment of all vehicles matches in terms of technical functionality like driver assistance systems and infotainment. All design related options are neglected, since they are subjective to the buyer's taste and therefore do not serve any practical use but would only increase the vehicle's purchase price. The vehicles used in the following are summarized in Table A1.

3.2. Total Cost of Ownership Calculation

To calculate a passenger vehicle's TCO, an overview of the used values and assumptions needs to be given. This paper uses three main categories of costs, namely one-time costs, reoccurring costs and mileage-dependent costs. These categories are explained in the following.

3.2.1. One-Time Costs

At the beginning of a vehicle ownership, it is usually purchased from the manufacturer or a dealership with either a one-time payment or a form of financing option. Since a full-price purchase is mostly the cheapest option, because no financing service is causing extra costs, only this option will be considered in this paper. Although some car dealerships offer special prices and discounts at various times of the year, each vehicle's listing price will serve as purchase price. This will prevent strong deviations during the data acquisition process. To make the different vehicle options as comparable as possible, the vehicles' purchase price will be determined with similar peak motor power and optional extras, depending on the vehicles' segment and the best-in-class equipment.

At the time of conducting this study, in Germany an environmental bonus can be requested from the Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA) for BEVs and FCEVs. This financial benefit is used to make BEVs and FCEVs more competitive to conventional ICEVs in terms of purchase price [46]. This environmental bonus can be requested once for each vehicle and will be considered in this study. The exact value of the bonus is 4500 € for vehicles with a net listing price less than 40,000 € and 3000 € for vehicles with a net listing price between 40,000 € and 65,000 €. In addition to that, the manufacturer is obligated to grant an additional bonus on the purchase price amounting to 50% of the BAFA environmental bonus [47].

With the vehicles' decommissioning after 230,000 km or 16 years, the remaining value will be considered with 0 €. Although there is still value within the vehicles through spare parts, scrapping often is offered with no additional costs for the consumer in return. However, it can be expected that the batteries present in BEVs still retain a part of their value, since they are expected to have a significantly longer lifetime than the rest of the vehicle [48]. Therefore, vehicle decommissioning would not be necessary in many cases. However, for better comparability, it is assumed that the BEVs are decommissioned anyways, with the respective battery's residual value being paid back. In the future, as traction batteries are becoming even better than today in terms of lifetime, this discrepancy in vehicle service life will significantly impact the TCO calculations. In this study, this aspect is dealt with as described to reduce complexity. According to [49], in 2040, second-life batteries will have a 25% cost advantage over new batteries. To calculate the remaining financial value of the batteries, the remaining battery capacity needs to be calculated. Firstly, the total distance traveled is used to calculate a battery cycle count at End-of-Life (EoL). The distance is divided by the range stated by the manufacturer for each vehicle, measured through the WLTP. Secondly, the cycle count is calculated to analyze the remaining battery capacity. A linear capacity degradation is assumed, which is sufficiently accurate for the purposes of this investigation. Using the battery aging tests with WLTP stress profiles performed by [50] for Nickel-Manganese-Cobalt-Oxide (NMC) batteries and by [51] for Lithium Iron-Phosphate (LFP) cells, a capacity based State of Health (SoH) of 70% is usually experienced after 2000 full equivalent cycles in BEVs. Accounting for calendar aging, as investigated by [52] for Nickel-Cobalt-Aluminium-Oxide (NCA) and by [53] for LFP battery cells, this study assumes an SoH of 70% after 1000 full equivalent cycles for the vehicle batteries, regardless of their type. As stated by [54], the battery prices will drop to 92 $ per kWh in 2040, which is approximately 85 € at this time. With the reduction of 25% due to being

second-life batteries, a financial value of approximately 64 € per kWh of remaining battery capacity is assumed. Finally, the remaining battery value at the vehicles' EoL is calculated with the battery capacity at EoL and the expected financial value per kWh.

3.2.2. Reoccurring Costs

In contrast to one-time costs, reoccurring costs have to be paid yearly by the vehicles' owners. In Germany, a passenger vehicle tax needs to be paid for each vehicle that is registered. This tax is strongly dependent on the type of energy source and the CO_2-emissions. For instance, a gasoline powered vehicle with an engine displacement of 1999 ccm and CO_2-emissions of 100 g per kilometer costs 50 € per year while a similar diesel powered car costs 200 € and a BEV or FCEV costs 0 € for the first ten years of registration or until 2030 [55]. Afterward, the tax for BEVs and FCEVs is calculated depending on the vehicles' maximum allowed mass. All vehicle taxes are calculated with [55] for this investigation.

In addition to the vehicle tax, a liability insurance is obligatory for passenger cars in Germany. Partial and fully comprehensive insurance, however, are also options that many vehicle owners choose, especially with new cars [56]. The insurance rate is strongly dependent on the vehicle itself, but also the insurance policy holder as well as the group of persons who are allowed to drive the vehicle. Since every insurance company charges different rates the data acquisition process is complex. For this reason, the insurance rates for an average vehicle owner are calculated with the online calculator provided by the largest vehicle insurance company of Germany [57]. The average vehicle owner defined for this investigation starts with a new insurance policy, is born in 1978 (45 years old) [58], lives in 85579 Neubiberg, Germany and chooses a full-year policy. The vehicle is fully paid, the owner does not have a home ownership [59], drives 15,000 km per year and uses the vehicle mainly to commute to work. All drivers over 25 years of age shall be insured. The owner has a Damage-free class (German: 'Schadensfreiheitsklasse') (SF) of 20 [60] and chooses a deductible of 150 € and 500 € for partial and full comprehensive insurance, respectively. With these assumptions, the cheapest insurance option is chosen for each vehicle.

Since 2022, BEVs that are registered in Germany can register for the GHG reduction quota. It is assumed that a BEV reduces the emitted amount of GHG compared to ICEVs by 837.6 kg per year [61]. Thus, mineral oil companies must buy the reduction quota from the owners of BEVs to reduce their individual GHG emissions by up to 25% until 2030 [62]. Although the CO_2 certificate price is expected to increase to about 600 € per ton of CO_2, the quota is not directly linked to the certificate price and will, further, soon be partially fulfilled by fuel and energy companies through the use of other sustainable energy sources [61]. Therefore, the yearly value of 300 € will be used for the GHG reduction quota within this investigation.

Finally, the opportunity cost of interest can be added to the reoccurring costs of a vehicle. This means that the amount of money spent on the vehicle could have been invested otherwise into stocks etc. Therefore, the interests or return on investment are not earned by the vehicle owner. On the other hand, by investing into a vehicle, inflation does not influence the value of the vehicle at the time of the purchase but would indeed reduce the interest profitability of an investment. Since both effects are difficult to express and compare in figures and would therefore exceed the scope of this paper, they are omitted.

3.2.3. Mileage-Dependent Costs

The yearly reoccurring costs as described in Section 3.2.2 can vary by a small amount every year but are expected not to not vary by a large amount. Mileage-dependent costs,

in contrast, can vary greatly depending on the inspection policies of the vehicle manufacturers, the tire size and type, the warranty period a manufacturer offers, etc. However, the greatest factor of influence will most certainly be the development of energy prices. Frankly, this is also the influence with the highest degree of uncertainty. To keep the data acquisition process as comprehensible as possible, the costs for vehicle inspection, repairs, and other costs due to vehicle mileage are taken from [63]. Fuel and energy costs are calculated as follows: The average prices for gasoline, diesel and electricity since the beginning of records in Germany are depicted in Figure 1.

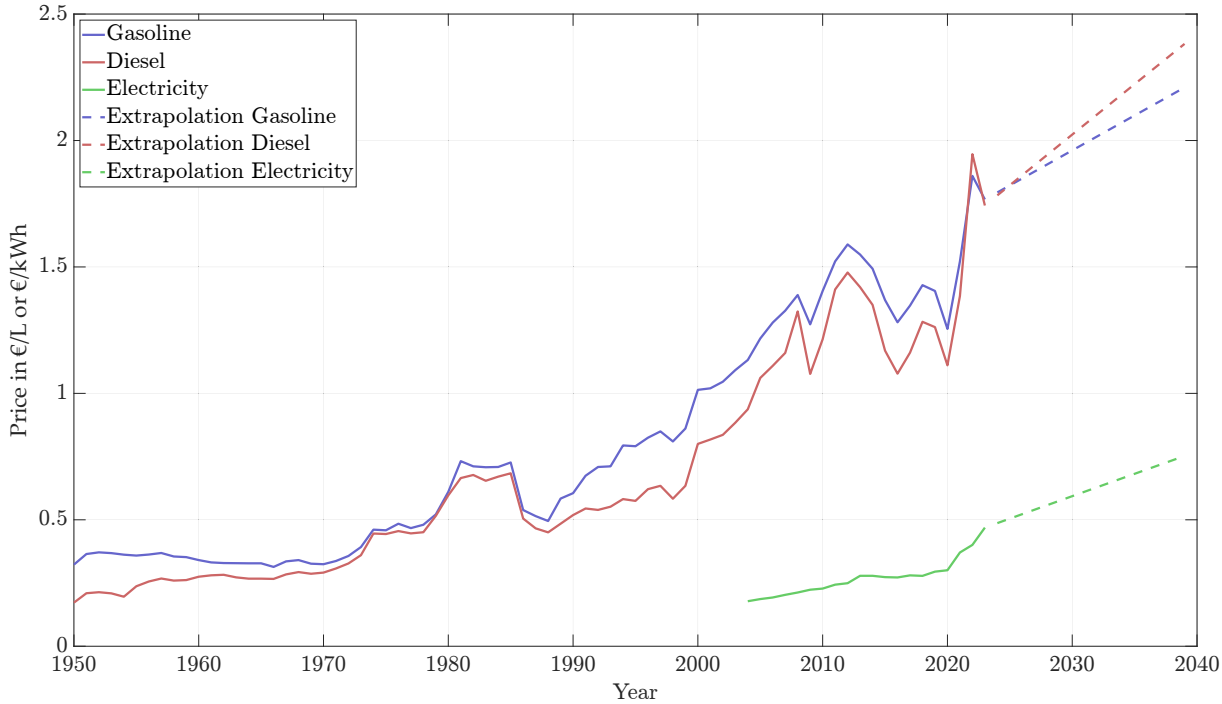

Figure 1. Prices for gasoline, diesel and electricity since the beginning of records in Germany. Quadratic extrapolation until 2039. Values before 2001 were converted from Deutsche Mark into Euro [64–66].

The quadratic extrapolation shows the respective prices until 2039 if the trend continues. To receive an average price for the future 16 years of vehicle usage, we calculated the arithmetic mean for each energy source. Since hydrogen stations are still rare in Germany and hydrogen is mainly produced from natural gas steam reforming (gray hydrogen), the price is strongly dependent on the price for natural gas. Currently, the cost for hydrogen at refueling stations is about 14 € per kg. In 2022, the cost for natural gas was on average 0.0844 €/kWh [67]. With an extrapolation of the price indices for natural gas, when supplied to trade and commerce from 2005 to 2022 [67], an increase in price to 15.78 €/kg will be used for hydrogen costs within this investigation. This value is in accordance with the predictions of the hydrogen production costs made by [68]. The applied mileage-dependent costs for each energy source are summarized in Table 2.

Table 2. Mileage-dependent costs for each fuel/energy type under consideration.

Fuel/Energy Type	Value	Unit
Gasoline	2.00	€/L
Diesel	2.08	€/L
Electricity	0.62	€/kWh
Hydrogen	15.78	€/kg

3.3. External Cost Calculation

The external costs that occur from vehicle usage generally can be divided into two distinct categories: positive and negative external costs. Positive external costs are those that are usually anticipated and therefore are subject to previous research as described in Section 2, e.g., costs from air pollution and GHG emissions. However, negative external costs are equally important but often overlooked. These are mainly tax revenue for countries and communities, which can serve a greater good when being redistributed into social and sustainable projects. Since taxes can be redistributed within the authorities in Germany and are not purpose-bound, this paper assumes that all government spending has a positive social impact [69]. However, this is only a necessary assumption, which cannot be proven to occur in every country or community. The actual benefits cannot be properly quantified unless an actual overview of governmental spending for each community is reviewed. In Germany, however, governmental spending can be precisely quantified. As investigated by [70], the vast majority of tax revenue is used to create a positive social impact. Furthermore, investments in road infrastructure, which mostly serves better individual road traffic, is low. Therefore, vehicle tax revenue is hardly being used for its own purpose, which reduces the risk of potential double-counting. Additionally, the negative external costs hardly directly outweigh the positive external costs. For instance, building a municipal regenerative power plant using vehicle taxes cannot reduce already emitted amounts of GHG emissions from fossil fuels in ICEVs. Regardless, it will reduce GHG emissions in the future and therefore reduces the overall external cost. Although the classification as 'negative' is used for better comparability, they can be seen as 'positive for society' since the overall external costs are reduced.

3.3.1. Positive External Costs

The environmental costs of a passenger vehicle can be taken over from [71,72], which focus on emissions and land use. While the CO_2 emissions of each vehicle are calculated similar to [73] and accounting for a linear reduction of GHG emissions for electricity production, the land use is generalized for all vehicles. This is reasonable since with respect to the space for driving and parking, a passenger car hardly differs in terms of vehicle size and energy source. Therefore, roughly the same space is covered through roads, etc.

Due to ethical reasons, the welfare of present and future generations is equally weighted within this study. Therefore, the recommendations made in [71,72] for a 0% pure time preference rate are taken over as value factors for the environmental cost value factors. If values are given for multiple years in the future, a linear interpolation is performed, and the mean value is used. These assumptions lead to the overall value factors given in Table 3.

Table 3. Environmental cost value factors [72].

Impact Factor	Value	Unit
GHG emissions	703	€/t CO_2
Gasoline ICEV exhaust air pollution (excl. CO_2)	736	€/vehicle
Diesel ICEV exhaust air pollution (excl. CO_2)	3611	€/vehicle
Land use and fragmentation	828	€/vehicle
Air pollution through abrasion	69	€/vehicle
German environmental bonus	4500/3000/0	€/vehicle

The values for air pollution by exhaust gas cannot be generated for each of the different vehicles, unless each vehicle is measured with a respective test setup. Since this is not possible within the scope of this paper, the generalized values are taken over from [72]. The standard vehicle for gasoline emits 153.7 g of CO_2 per km, while the diesel vehicle emits 131.6 g of CO_2 during operation when only accounting for tank-to-wheel emissions. Both

values are reasonable for average ICEVs, so it is assumed that the values for air pollutants through exhaust gas are conclusive. Similar to [72], the values for noise generation were neglected due to the difficulties of comprehensive data acquisition.

In contrast to [74], this investigation does not include vehicle accidents into the external cost calculations. Firstly, there is insufficient information about the calculation basis for the value of vehicle accidents and the influence of injuries as well as environmental destruction through leaks, fires, etc. Secondly, all costs related to vehicle accidents are covered by insurance companies, which are mostly private. The insurance fees paid by the vehicle owners therefore already cover the occurring costs of vehicle accidents. The costs for congestion and noise were purposefully omitted since they cannot be properly linked to individual vehicles and would most likely not differ between models.

When passenger cars are actively funded via purchase bonuses like the German environmental bonus, the amount of money provided by the government to purchase the vehicle cannot be used for other social purposes. Therefore, external costs are increased. In contrast to government funding, the GHG reduction quota has no impact on external costs. Although it is often believed that this quota increases the amount of CO_2 certificates circulating, this is not the case, since the EU's CO_2 certificate trading is not related to the GHG reduction quota [75]. Therefore, the quota is solely a trade between mineral oil companies and the owners of BEV, so no external costs emerge.

3.3.2. Negative External Costs

Contrary to other external cost investigations, this paper includes the potentially positive effects of tax income on the society. This source of governmental income includes the general value added tax of 19% on the purchase price and the reoccurring costs, the insurance tax of 19%, the passenger vehicle tax and the fuel tax as well as the electricity tax.

In Germany, the Value Added Tax (VAT) per liter of petrol at a retail price of 2.00 € is 0.32 €. According to [76], the mineral oil tax accounts for 0.50 €, the eco tax amounts to 0.15 € and the CO_2 tax is responsible for 0.08 € per liter. Overall, 1.06 € (rounding included) per liter of gasoline are collected in the form of taxes. Diesel is responsible for a value added tax income of 0.33 € per liter. The mineral oil tax is 0.32 €, the eco tax is 0.15 € and the CO_2 tax is 0.10 € per liter. This adds up to a total tax revenue of 0.90 € per liter diesel. The taxes on electricity are mainly the value added tax and the electricity tax. With an average price of 0.62 € per kWh, the value added tax is 0.10 €, whereas the electricity tax is 0.04 €. A total of 0.14 € per kWh can be accounted for negative external costs. Hydrogen does not underlie the German energy tax. Therefore, only the value added tax needs to be paid which is 2.52 € per kg.

3.4. Data Acquisition

The data acquisition process necessary to collect all relevant information can be described as follows:

Initially, all vehicle data relevant to the total life cycle CO_2 emissions were collected, similar to [73]. The values for vehicle mass, fuel or energy consumption, battery capacity etc. were obtained from the manufacturers' websites and information brochures, wherever possible. Missing data was taken over from vehicle database websites like [77].

The TCO related data was collected mainly through the same manufacturers' websites. The vehicles' purchase price was determined through intensive study of the price structure of every relevant vehicle within the same segment. Therefore, vehicle configurators as well as price lists and the standard configuration of every vehicle was investigated. All vehicles were configured to match the best-in-class standard configuration. In many cases, the delivery fee had to be investigated separately. Depending on the minimum net purchase

price of the vehicles, the governmental subsidies were calculated. The energy or fuel cost was calculated using the official WLTP consumption values from the manufacturers' websites. Insurance cost was collected via the calculator provided by [57], while the cost for inspection etc. was taken over from the database provided by [63]. The vehicle tax was calculated using the vehicle data obtained from [77] and the calculator provided by [55].

The necessary data for the calculation of the external cost components was already included within the TCO related data. The calculations were performed as described in Section 3.3.

To sum up this section, all further vehicle non-specific assumptions made for this work are summarized in Table 4.

Table 4. Vehicle non-specific assumptions for the TCO investigation.

Name	Value	Unit	Source
Country under investigation	Germany	–	–
Total vehicle lifetime in distance	230,000	km	[73]
Total vehicle lifetime in time	16 (rounded)	a	[73]
Years under consideration	2023–2038	–	–
Vehicle financing	Purchase	–	–
Insurance	Fully comprehensive	–	–

4. Results

The results are presented in the following section, starting with the sample calculation and concluding with the vehicle comparison.

4.1. Exemplary Calculation

An exemplary calculation of the TCO and external costs for a Tesla Model 3 is performed within this section. The BEV is used, so all potential influences on the cost assessment are included into the example.

4.1.1. Total Cost of Ownership Results

At the time of the data collection, in June 2023, a Tesla Model 3 RWD costs 42,970 € including the manufacturer's share of the environmental bonus (2250 €) and the delivery fee (980 €). The full 4500 € environmental bonus is applicable for this vehicle, therefore this amount reduces the TCO calculation. After decommissioning, the vehicle will have traveled 230,000 km. With a WLTP range of 491 km, the battery will have experienced 468 charging cycles and therefore have aged to an SoH of 86%. With a gross battery capacity of 62 kWh, a remaining EoL battery capacity of 53.3 kWh can be assumed. Therefore, the residual vehicle value is calculated to 3410 €.

The vehicle tax for a Tesla Model 3 is 0 € for the eight years 2023 until 2030. For the years 2031 until 2038, 62 € per year are to be paid, since the vehicle has a maximum allowed mass of 2149 kg. Based on the assumptions made in Section 3.2.2, the vehicle insurance is calculated to 662 € per year. Within 16 years of vehicle usage, a total cost of 10,592 € is added to the TCO. Reducing yearly costs for the vehicle, the GHG reduction quota with the amount of 300 € per year is used. The TCO is therefore reduced by a total of 4800 €.

The mileage-dependent costs due to vehicle inspection, repairs, and other costs are given with 85 € per month. Over the course of 16 years, a total of 16,320 € in costs are incurred. With the assumed 0.62 €/kWh for electricity, and a WLTP vehicle consumption of 14.4 kWh/100 km, total energy costs of 20,534 € are calculated for the vehicle life cycle of 230,000 km. The overall TCO components for the Tesla Model 3 RWD are summarized in Table 5.

Table 5. TCO components for the Tesla Model 3 RWD.

Cost Component	+/−	Value	Unit	Lifetime Total
Purchase price including manufacturer's share of the environmental bonus	+	41,990	€	41,990 €
Delivery fee	+	980	€	980 €
Environmental bonus	−	4500	€	−4500 €
Remaining value	−	3410	€	−3410 €
Vehicle tax	+	62	€/a	496 €
Insurance	+	662	€/a	10,592 €
GHG reduction quota	−	300	€/a	−4800 €
Inspection etc.	+	85	€/m	16,320 €
Electricity	+	8.93	€/100 km	20,534 €
Total cost of ownership	+	0.34	€/km	78,202 €

Adding up all the above mentioned TCO components, a vehicle TCO of 78,202 € is received for the Tesla Model 3 RWD. With this value, a kilometer-based TCO of 0.34 €/km can be calculated.

4.1.2. External Cost Results

The external costs for the Tesla Model 3 RWD are calculated according to the value factors given in Section 3.3.

With the assumptions that the vehicle has a curb weight of 1825 kg and a gross battery capacity of 62 kWh while having a WLTP energy consumption of 14.4 kWh/100 km, the total life cycle CO_2 equivalent emissions can be calculated to 15,873 kg, according to [73], with the mean standard energy mix interpolated until 2039, resulting in 0.339 kg/kWh. The external cost can therefore be calculated to 11,159 € for the occurring CO_2 equivalent emissions. The cost values for land use and fragmentation, as well as air pollution through abrasion, are taken from Table 3. For the sake of completeness, they are listed as two separate cost components here, but are combined afterwards, since they are equal for each vehicle. Similarly, the environmental bonus and the GHG reduction quota are adopted. The manufacturer's share of the environmental bonus is not taken into account since it has no social value, but rather a pure financial (negative) value for the manufacturer.

Negative external costs start with the 19% value added tax on the purchase price, including the delivery fee. This is taken into account with 6860.76 €. The vehicle tax in total of 496 € as well as 19% of the insurance fees and the inspection costs are added. Finally, the taxes on electricity are accounted for. It should be noted for better comprehensibility that the 19% tax is added onto the net prices, which leads to a value of 16% of the gross prices.

In total, the external costs for the Tesla Model 3 RWD are calculated to 9,686.85 € or 0.04 €/km, respectively, as can be seen in Table 6. This value can now be compared to other vehicles in order to explore their influence on society measured in external cost.

4.2. Vehicle Comparison

A vehicle comparison can either be done within a specific vehicle segment or for all vehicles in question at once. This section is therefore divided into two subsections. In Section 4.2.1, the vehicles are compared within their respective vehicle segment. In contrast, Section 4.2.2 gives a broader overview over the complete market.

Table 6. External cost components for the Tesla Model 3 RWD.

Cost Component	+/−	Value	Unit	Lifetime Total
Total CO_2 equivalent emissions	+	11,159	€	11,159 €
Land use and fragmentation	+	828	€	828 €
Air pollution through abrasion	+	69	€	69 €
Environmental bonus	+	4500	€	4500 €
GHG reduction quota	+	588.83	€/a	9421.28 €
VAT on purchase price and delivery fee	−	6860.76	€	−6860.76 €
Vehicle tax	−	62	€/a	−496 €
Insurance	−	105.70	€/a	−1691.16 €
Inspection etc.	−	13.57	€/m	−2605.71 €
Taxes for electricity	−	2.02	€/100 km	−4636.80 €
Total	+	0.04	€/km	9686.85 €

4.2.1. Vehicle Segments

Starting with a specific segment's assessment, the E segment is chosen for a detailed observation, since vehicles with all investigated energy sources are available there. The individual cost components are shown in Figure 2. As mentioned, the cost components for land use and fragmentation as well as air pollution through abrasion are combined and labeled 'LU + AP' within the figure legends.

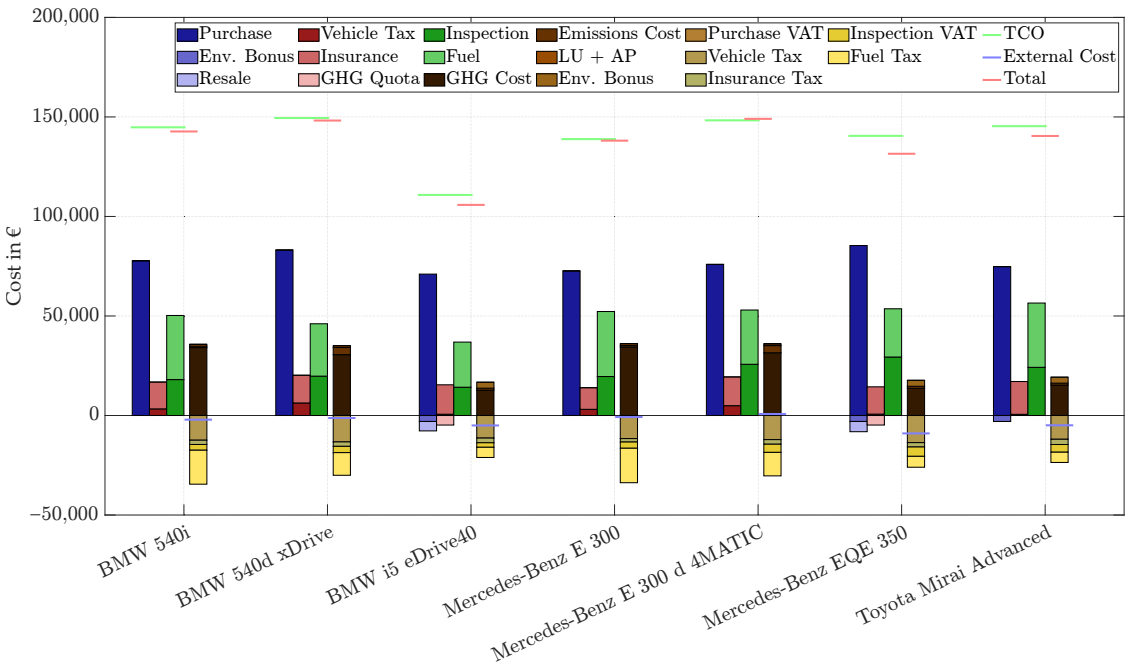

Figure 2. Cost components for vehicles in the E segment.

As can be seen, the purchase prices are in the range of approximately 70,000 € to 85,000 € with the BMW i5 eDrive40 being the cheapest with 71,040 € and the Mercedes-Benz EQE 350 being the most expensive with 85,400 €. The sole hydrogen powered vehicle's purchase price is close to most of the ICEVs. Since the BEVs and the FCEV are granted an environmental bonus by the state, each of them receives savings of 3000 €. Additionally, the batteries used in the BEVs will outlive the 16 years of time under investigation. This leads to a resale value of 4733 € or 5139 € for the BMW i5 eDrive40 or the Mercedes-Benz EQE 350, respectively.

Over the course of 16 years, the vehicle tax is 600 €–700 € for the BEVs and sightly over 3000 € for both of the gasoline powered vehicles. The highest vehicle tax needs to be paid by the diesel ICEVs with 6304 € for the BMW 540d xDrive and 4944 € for the Mercedes-Benz E 300 d 4MATIC, respectively, while the FCEV is the cheapest with

592 € during the whole vehicles' lifetime. The insurance cost has a low deviation between the vehicles, however, the Mercedes-Benz E 300 is the cheapest with 10,856 € and the Toyota Mirai Advanced is the most expensive with 16,486 €. The last part of the reoccurring costs is the GHG quota, which is only requestable for BEVs.

The inspection cost ranges from 14,208 € for the BMW i5 eDrive40 up to 29,376 € for the Mercedes-Benz EQE 350. The fuel cost lies between 22,673 € for the BMW i5 eDrive40 and 32,660 € for the Mercedes-Benz E 300.

The TCO is lowest for the BMW i5 eDrive40 with 110,809 €, followed by the Mercedes-Benz E 300 with 138,853 €, the Mercedes-Benz EQE 350 with 140,490 €, the BMW 540i with 144,789 €, the Toyota Mirai Advanced with 145,362 €, the Mercedes-Benz E 300 d 4MATIC with 148,291 € and finally by the most expensive, the BMW 540d xDrive with 149,451 €.

When investigating the external cost for all vehicles within the E segment, it can be seen that environmental costs differ strongly between energy sources. As expected, in addition to the significantly higher CO_2 emissions from fossil fuels, environmental damage through other pollutants results in higher external costs. However, due to the purchase bonus for BEVs and FCEVs as well as overall higher direct costs, ICEVs score better in the rest of the external costs due to tax revenue. Overall, however, the emissions generally outweigh the other factors. The lowest external costs are produced by the Mercedes-Benz EQE 350 with −8991 € and the BMW i5 eDrive40 with −5002 €, followed by the Toyota Mirai Advanced with −4928 €. The ICEVs from BMW are next with −2090 € for the BMW 540i and −1264 € for the BMW 540d xDrive. The ICEVs manufactured by Mercedes-Benz produce the highest external cost within this segment's comparison. Their values are −770 € for the Mercedes-Benz E 300 and 745 € for the Mercedes-Benz E 300 d 4MATIC.

Regarding the other vehicle segments, the respective cost components are depicted in the Appendix B Figures A1–A11. It becomes clear that BEVs always cause the lowest amount of external costs when compared to their ICEV counterparts. This is obvious, since the cost savings through significantly reduced emissions have the greatest impact on the external cost. Although the one-time costs are often higher, through the accumulation of reoccurring and mileage-dependent costs, BEVs are also often the cheapest vehicles related to TCO within their vehicle segment. Especially when comparing vehicles from the same manufacturer, this is always the case.

Within the E segment, it is shown that, for instance, a BMW i5 eDrive40 reduces the TCO compared to a BMW 540d xDrive by 26% or 38,642 € while the external cost is reduced by 3738 €. The most extreme case of external cost reduction can be found within the E-SUV segment (see Figure A8), where the Mercedes-Benz EQE SUV 500 4MATIC reduces the external cost by 14,300 € compared to the Mercedes-Benz GLE 450 d 4MATIC.

4.2.2. Vehicle Market Overview

In Section 4.2.1, it already became clear how the different energy sources can be compared within individual vehicle segments. Whether the expected trend is true for the complete vehicle market will be elaborated within this section. A comparison of the TCO, external cost investigation results across all vehicle segments and fuels is depicted in Figure 3.

Each vehicle segment is marked with a distinct symbol, and each energy source is colored differently within the plot as described in the figure's legend. Individual data points are complemented by a dashed line that shows a quadratic interpolation within each energy source. This dashed line serves as an approximation which TCO and external cost occur for other vehicles with the same energy source. It becomes clear that the TCO as well as the external cost results obtained in Section 4.2.1 can likely be extrapolated for all consumer vehicles in the market, if the same assumptions as described in Section 3.1 are

made. Due to the limited number of data points of FCEVs, no interpolation was performed for this energy source.

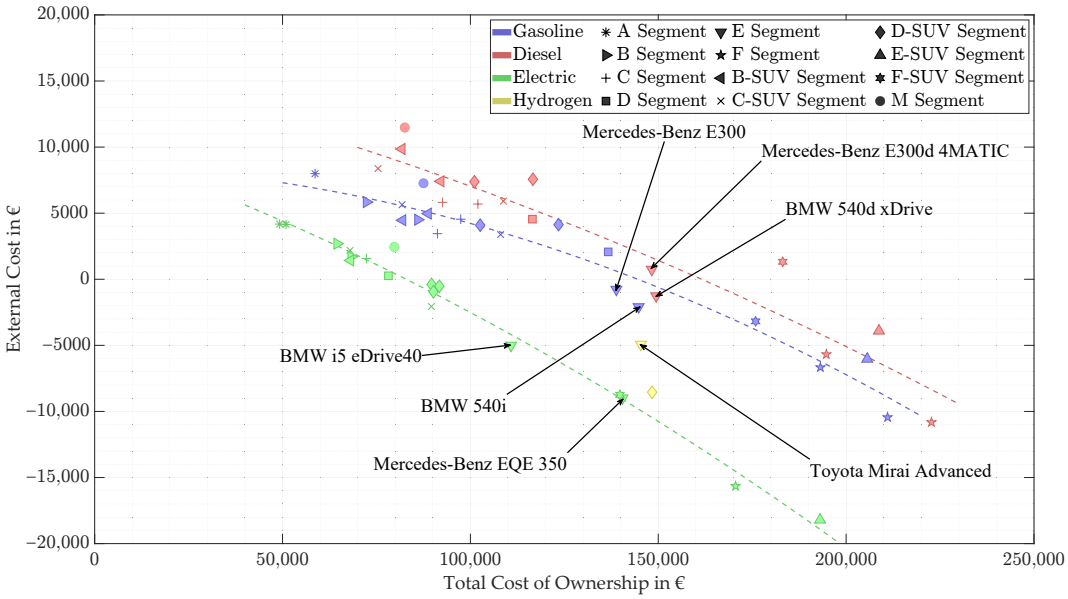

Figure 3. TCO and full external cost across all vehicles within this study.

The lowest TCO over all segments can be achieved with BEVs in the A segment. Regardless of the vehicle segment, BEVs always have the lowest TCO, followed by FCEVs. Diesel ICEVs have the highest TCO. While gasoline ICEVs in lower vehicle segments are significantly lower in TCO as well as external cost compared to diesel ICEVs, the difference decreases with increasing vehicle segment. When increasing the vehicle size, it can be observed that the rise in TCO is generally less significant when staying within the same segment and switching to an SUV, compared to moving up to a higher vehicle segment.

The lowest external cost can be achieved with BEVs, similar to the TCO. While all vehicles in the lower segments have positive external costs, BEVs around the D and D-SUV segments and above generate more value than harm to society, when using the assumptions as described in Section 3. This is also the case for all FCEVs available at the moment. Due to the high external cost through pollution from diesel fuel, diesel ICEVs generally cause higher external cost than comparable gasoline vehicles. For ICEVs, starting around the E segment, the tax revenue exceeds other external cost components so that the total external cost becomes negative.

To set the TCO related results into perspective, the purchase prices and base prices of all vehicles under consideration are depicted in Figure 4. All round markers represent the purchase price of the vehicles found in Table A1 including their considered additional equipment. The color scheme was taken over from Figure 3 for consistency. Each vehicle's base price is given by the low point of the error bar. As previously described and in contrast to popular beliefs, equally equipped vehicles within the same segment are mostly similarly priced. In most segments, BEVs are not significantly more expensive to purchase. In some cases, such as the C, D and F-SUV segment, BEVs are already the cheapest option at purchase. However, the popular belief that BEVs and FCEVs are more expensive to purchase can be explained by a comparison of the base prices. In all segments but the F, E-SUV and F-SUV segments, BEVs and FCEVs have higher base prices than their ICEV competitors. This is partly due to the large differences in vehicle equipment at starting price. While ICEVs can often be purchased with low-powered engine variants and no extra equipment, BEVs often only offer few high-powered motor variants and an extensive standard equipment. This leads to the described base price to purchase price discrepancy.

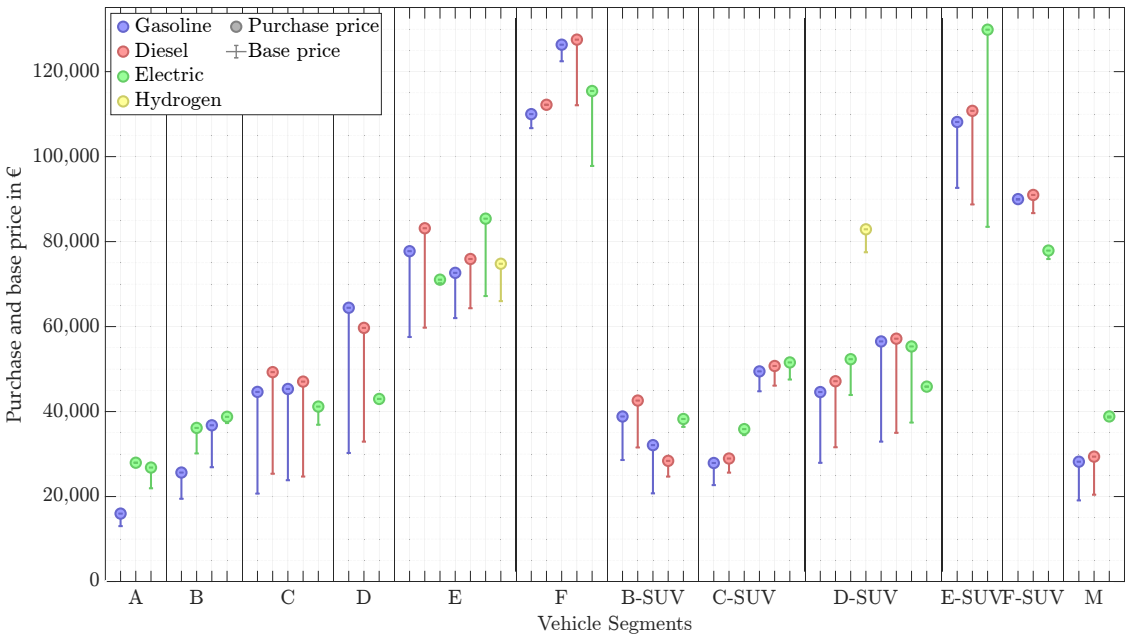

Figure 4. Base price and actual purchase price of the vehicles used within this study.

Across all 55 analyzed vehicles and 12 segments, the results reveal a consistent and clear pattern: battery electric vehicles show the lowest TCO in every segment, primarily due to reduced energy and maintenance costs and, where applicable, purchase subsidies, while diesel ICEVs consistently exhibit the highest lifetime costs. The external cost analysis likewise shows that BEVs generate the lowest external cost across all segments, mainly because of substantially lower life cycle GHG emissions, whereas diesel ICEVs produce the highest external costs. Differences between manufacturers and segments can largely be traced back to structural cost drivers such as energy consumption, taxation and equipment-related base price effects rather than drivetrain-specific anomalies. Taken together, these findings demonstrate that drivetrain choice has a stronger influence on TCO and external cost than vehicle segment, and that BEVs represent the most cost-efficient and environmentally friendly option within the current German passenger vehicle market.

5. Discussion

This section discusses the results obtained in Section 4. It sets the results into perspective while focusing on the difference between TCO and external costs. Furthermore, the problems that occurred during the data collection and processing are described.

5.1. Discussion of the Results Obtained

As shown in the results, the common conception that BEVs are higher in their purchase price compared to their ICEV counterparts is true for vehicles in the C segment and below. However, the environmental bonus often can reduce the price difference by a significant amount. This finding is surprising but can be easily explained by the fact that the minimum vehicle equipment for BEVs includes more features than the standard equipment for ICEVs. Since this paper compares similarly equipped vehicles, the effective price difference is lower for equivalent cars.

As expected, the total external cost is lowest for BEVs, mostly due to the reduction of GHG emissions. In comparison to diesel ICEVs, a significant reduction of other emissions is also observable. However, since BEVs generate lower overall tax revenue due to their lower TCO, this lead is partly reduced.

According to the results obtained within this study, all passenger vehicles cause significant external cost due to environmental damages and partly through governmental financial support. While the external cost through GHG emissions is by far the largest component, the second largest is air pollution for ICEVs and the Environmental Bonus for BEVs and FCEVs, respectively. Although the external costs are high, in many cases the generated tax revenue can exceed the environmental damages in terms of cost. Especially with vehicles within higher segments, the emissions rise slower than the vehicle costs, leading to lower overall external cost through higher tax revenue. For ICEVs, the fuel tax is the largest negative external cost component, while for the other vehicles, it is the VAT at purchase. In general, it can be said that the more expensive a vehicle is in TCO, the better it is for a society due to the lower external cost, since this theoretically leads to a redistribution of money from rich to poor. Finally, for external costs, it must be mentioned that external costs for congestion and accidents were neglected and that no vehicle would have net negative external cost (positive effect on society) if these were included. In Addition to that, tax revenue was fully calculated as negative external cost. However, while the vast majority of tax income in Germany is used for social purposes, security services, education and health services, a 100% efficiency in governmental spending is unlikely.

Another interesting finding is that different vehicle manufacturers have different pricing structures within their lineup. In some cases, such as BMW, BEVs appear to be comparable in purchase price to the equally equipped ICEVs, since the manufacturer partially forgoes the margin on optional equipment for electric vehicles. It is also possible that BMW's BEVs are generally comparable in production cost since most of their vehicles use the same platform, regardless of the drive train. In addition, BMW manufactures components like the electric motors in-house. This leads to lower purchase prices. In other cases, for instance with Mercedes-Benz, BEVs are significantly higher in purchase price, leading to a higher TCO compared to gasoline ICEVs in the E segment. Compared to BMW, Mercedes-Benz uses different vehicle platforms for ICEVs and BEVs in higher vehicle segments and the production of major components such as the electric motors are outsourced to suppliers. This might partially explain the differences in purchase prices between the manufacturers. However, it is also possible that the manufacturers simply aim for different market positioning with their vehicles. In most cases, BEVs are priced higher than comparable ICEVs but at the same time low enough that the TCO is lower. Due to this, brand loyal consumers might be tempted to choose different drive trains depending on the manufacturer. When looking at the base prices of the vehicles under consideration, it can be seen that, in most cases, ICEVs are priced lowest in their respective segments. This can be explained by the differences in selectable vehicle equipment and drive power. Since BEVs are expected to be more expensive to produce, vehicle manufacturers likely offer an extensive base equipment to justify the higher purchase price. However, by offering the same base equipment as for the ICEV counterparts, the base prices for BEVs could be further reduced and consumers would not have to pay for equipment that they normally would not order. The large differences in base price and actual purchase price with the desired additional equipment might not be obvious to many consumers since manufacturers' pricing information only states the vehicles' base prices, in most cases. This leads to the perception that BEVs are generally more expensive. All of this leads to a high amount of responsibility for vehicle manufacturers when building a pricing structure. Nevertheless, it can be expected that BEVs will be chosen more often in the future due to their lower TCO.

Due to the classification of the specific vehicles into their vehicle segments, it is also interesting to see that for instance, the vehicles in the E-SUV segment have a higher TCO compared to the formally higher classified F-SUV. This leads to inconsistencies in the

comparison of different vehicle segments. However, the full vehicle comparison is not affected by this.

When comparing gasoline and diesel ICEVs, it becomes clear that diesel vehicles are becoming less attractive due to their higher TCO. In most cases, the external cost of diesel vehicles is also higher, mainly due to the higher external cost through air pollution.

Finally, it has to be mentioned once more that this study only includes two FCEV models. This is due to limited availability of FCEVs in the German market. Therefore, the small sample size limits the generalizability of FCEV findings.

5.2. Comparison to Existing Research

The following provides an overview of the current state of research with regard to TCO and external costs.

5.2.1. Total Cost of Ownership Studies

Comparing this study's results with the results obtained by [18], it becomes clear that in that last eight years especially BEVs have become more common in the passenger car market. While in [18] gasoline and diesel vehicles were comparable in TCO, this is no longer the case. In addition, the large price premiums for BEVs and especially FCEVs seem to have vanished. This is mostly due to the fact that BEVs and FCEVs have become more affordable through bonuses and that conventional fuels have become more expensive.

In [20], although calculating their results for the USA, the authors obtained similar results compared to this study. Depending on the vehicles within the B segment, the purchase price difference between the ICEV and BEV can be as much as 40%, while [20] only used 16%. However, due to the longer usage period considered within this paper, the final TCO results are similar. In both cases, the BEVs have an overall lower TCO.

In contrast to [22], the present study found that not only small BEV can compete with their ICEV counterparts in terms of TCO. While [22] conclude that heavier, larger BEVs can only compete with conventional vehicles if the running costs are very low, this study shows that nowadays, BEVs already undercut ICEVs in TCO with realistic running cost assumptions. A possible explanation for the difference, apart from the changed vehicle market, is the hypothesis that batteries have a significantly longer lifetime than assumed by [22].

In [25], the authors focus especially on the running costs of the vehicles over the period of vehicle usage. Therefore, it is much more detailed within this part of the calculations. This depth of detail leads to a smaller variety of vehicles under consideration. However, the results are comparable with the ones obtained within this study. The difference in TCO between all drive trains for small SUVs is small in both studies. While [25] conclude that BEVs have a slightly higher TCO, the present paper comes to the opposite conclusion. This is most likely due to the subsidies available in Germany versus the ones offered in the USA.

Compared to the present study, [26] used modeled vehicles and omitted crucial cost components such as taxes and purchase bonuses. In addition, manufacturers' individual pricing strategies could not be included in their calculations. The results show, however, that especially BEVs with a low driving range reach TCO parity with a ICEV within a usual vehicle lifetime. While the minimum time to cost parity is about six years in [26], the present study found that, depending on the manufacturer's pricing, it can be an initial price advantage for BEVs. The largest difference in the results can be found for the BEV with 450 miles of range, represented by the F segment in this study. Although [26] state that TCO parity is achieved after 20–25 years, considering the correct curb weight, the present study found that BEVs already cause lower cost at purchase.

While [30] came to the conclusion that smaller and shorter range BEVs are more cost effective than their respective ICEV counterparts, whereas larger and longer range BEVs require subsidies, this is in contrast to the findings within our study. However, since most of the assumptions made in [30] strongly differ from the ones made in this study, the differences are expected.

When comparing the results of the present study to those of [32], it becomes clear that they are quite similar. While the purchase price of BEVs is very low in [32], it is also lower in the present study, in many cases. The lower utilization costs of BEVs increase the cost benefit even further. However, overall, the amount of TCO reduction cannot be compared properly since the time span under consideration is largely different between the two studies.

5.2.2. External Cost Studies

Comparing the results with [34], it becomes clear that the studies had different focuses. While this study's aim is to compare different vehicles, [34] compares different types of transport. However, the external cost components are comparable, although [34] focuses more on accidents and congestion. As described in Section 2.2, the present study neglected these external cost components, since it is unclear how and if they can be allocated to a single vehicle. The EU's handbook suggests, that 50% of the health costs, 30% of the costs for public service (police etc.) and 55% of the production loss cost caused through car accidents should be used for external cost calculations. However, no reason is given, and it is mentioned that these costs are paid for by insurances. Within [34], the external costs caused by accidents and congestion add up to 37,704 €. The largest difference can be found in external cost through GHG emissions. While this paper uses a cost factor of 703 € per ton of CO_2, the EU's handbook only uses 100 €.

According to [74], the external cost of transportation in Germany is 149,000,000,000 € per year, whereas about 94.5% are caused by cars and motorcycles. Neglecting the amount of motorcycles in use, a rough estimate with 49,100,000 passenger cars in the streets is that each vehicle causes external costs of almost 2900 € per year. This would result in about 45,900 € for the whole vehicle life cycle. While 54,600,000,000 € are given as the external cost caused by accidents alone for 2017, this value contradicts the value given by [78], which is only 35,700,000,000 €. Nevertheless, as previously described, it is unclear, if these external costs can be attributed to the passenger vehicles or if they are covered by insurances.

Respecting the fact that the present study does not include accidents and congestion as well as noise within its calculations, the results obtained by [35] vary by a large amount. While air pollution from gasoline cars is expected to cause 2.2 times the external cost, this factor for diesel cars is only 1.4. Land use is stated to cause 18 times the amount of external cost than calculated in this study. In contrast, the external cost caused by GHG emissions is calculated to only about 25–30% of the results obtained in the present study.

5.3. Limitations of This Study

The aim of this investigation was to generate a meaningful comparison between different vehicle segments and drive train types. Since the number of vehicles taken into consideration was larger than most comparable studies, some simplifications and assumptions needed to be made. In addition, problems occurred with data collection and processing.

The first simplification relating to TCO calculation is the focus solely on a single vehicle owner for the whole life cycle of the considered vehicles. In reality, it is more common to resell a new vehicle after a couple of years or buy a used vehicle, respectively. However, taking this into consideration would make the calculations unnecessarily more complex and

was therefore neglected. Since the purchase of a used vehicle typically involves a transfer of ownership between two individuals who utilize the vehicle sequentially, the transaction cost constitutes revenue for the seller and an investment for the buyer. Within the TCO calculation for the vehicle, however, the transaction cost does not appear. Further, this study provides a normative rather than descriptive analysis. A rational behavior regarding the decision-making process of the consumer is assumed, while emotional influences to decision-making like range anxiety, status, design or other personal preferences were neglected.

In Germany, a significant percentage of new vehicles is not bought but financed, leased or used as company cars. Although these might be reasonable options for owners, this would further complicate the calculations performed within this study. Changing interest rates or sales statistics of an individual car dealership can greatly influence the outcome and are not representative. Thus, this investigation only considered full vehicle purchase. Vehicle depreciation is often used to calculate a residual value of a vehicle at any given time. Since this study performs a TCO investigation, the residual value at the end-of-life of each vehicle is zero, with the exception of the battery pack. Changes in technology can influence the purchase prices dramatically. For instance, new battery chemistries can lead to lower manufacturing costs of BEVs and increasingly strict exhaust gas regulations will certainly cause higher development and manufacturing costs for ICEVs. However, since this investigation assumes a vehicle purchase in 2023, new technologies do not affect the outcomes of this study.

Within this investigation, the external cost due to air pollution was generalized for the different vehicle types. In reality, each vehicle has its own pollution values but the individual measurement and interpretation would exceed the scope of this paper. In the German registration documents, a noise value is given for all vehicles, but the value is measured under unusual circumstances, being full-power acceleration. Within the environmental damages, no further investigations were performed or considered. Although there is severe environmental destruction due to raw material production, only the GHG emissions can reliably be used for this study.

The lifetime of the vehicles under consideration is estimated to be similar, with an assumption of 16 years. At this time, it is not yet foreseeable whether the majority of BEVs will last this long without major repairs within the drive train. However, there are already occasional reports of BEVs with extraordinarily high mileage and studies that suggest a very long cycle life of Li-Ion batteries, as described in Section 3.2.1. In Addition, ICEVs often need repairs on major drive train components before they are finally decommissioned. This was also neglected due to uncertainty. For FCEVs, it is unclear whether important components like the fuel cell stack will work properly without any repairs until the vehicles' EoL. Given these arguments, it is reasonable to conduct the calculations as described. Nevertheless, the time horizon of vehicle usage may not correspond to consumers' actual decision-making horizon.

Another limitation of this study is the uncertainty of vehicles' usage profiles. While the calculations are based on the vehicles' fuel and energy consumptions as well as emissions determined with the WLTP, real-world values can differ largely depending on e.g., the type of driver, location of utilization etc. For instance, the impact of one-time costs as well as reoccurring costs is smaller with increased yearly mileage. Similarly, external costs of ICEVs are increased with total distance traveled, since the emission cost is the largest external cost component. While this is also the case with electrified vehicles, the quantitative effect is not as pronounced.

Within the external cost calculations, loss of potential working time due to congestion and charging time was not considered, since a reliable data acquisition is too complex and

too many factors influence this value. Furthermore, the use of company profits e.g., for social purposes or for unethical investments was not further investigated.

Vehicle purchase prices, purchase bonuses, etc. are under constant change at this time. In addition, fuel and electricity prices are volatile and greatly influence the results of this investigation. Although the prices are modeled in respect to their development over the past decades and include future predictions in taxation, it is uncertain how they will change over the time horizon in question. On average, the fuel and electricity costs are responsible for 26.5% of the vehicles' TCO, ranging from 13.3% to 44.0%. An error of 20% within the fuel and energy price prediction would therefore only lead to an average TCO increase of 5.3%. Since fuel and electricity tax is dependent on the respective price, external costs are also impacted by any changes. However, the taxes are only a fraction of the consumer prices. As we have seen in the past, unusual price increases generally affect all energy sources in a similar order of magnitude.

Since this study was conducted for Germany, not all findings might be applicable for other countries. Nevertheless, most European countries have comparable tax structures as well as subsidies. Given that the purchase prices do not differ extensively within Europe and in most countries the fuel and electricity prices are similar in relation to each other, the key findings should also be useful for readers from other countries. Generally, the methodology used within this paper is applicable for all countries worldwide, given that the underlying data for the calculations is available.

As previously described, the vehicles were assumed to be purchased as new at full price. Therefore, the second hand market was not considered, although many consumers in Germany buy used vehicles with significant discounts. However, since considering used vehicles would exclude the initial loss of value, no complete TCO and external cost calculations would be possible. This leads to the limitation that, when buying used vehicles, purchase prices and governmental subsidies change for the consumers and the results from this study could potentially change. At this point in time it is unclear how residual value differs between ICEVs, FCEVs and BEVs after different time periods of usage.

Another limitation of this study is the fact that infrastructure investments were not considered. While all vehicle users generally profit from investments in new roads, bridges, parking lots etc., only users of electrified vehicles profit from investments in charging infrastructure. Since it is difficult to find out to which extent charging infrastructure, which is mostly owned by private companies, is subsidized by the government, these investments were outside of this study's considerations.

6. Conclusions and Outlook

In this section, the findings of this paper are summarized and contextualized in the conclusion, and an outlook on further research on the topic is given.

6.1. Conclusions

This paper investigates the TCO and full life cycle external cost of currently available passenger cars in Germany. A total of 55 vehicles and variants within 12 vehicle segments were compared. Gasoline and diesel ICEVs as well as BEVs and FCEVs were considered in this investigation while other energy sources were neglected due to their low market share and uncertain forecasted significance within the next decades.

The TCO consists of one-time costs, like the purchase price, purchase bonuses and the resale value, reoccurring costs that are due yearly, like vehicle tax, insurance fees and the GHG reduction quota, as well as mileage-dependent costs, like vehicle inspection and fuel cost. The external costs are divided into positive and negative external costs. The positive

external costs consist of an estimation of various environmental damages as well as other costs for the tax payers while the negative external costs summarize mainly tax revenue.

The TCO ranges from about 50,000 € for the cheapest vehicle to over 220,000 € for the most expensive passenger car. It can be seen that, in contrast to general beliefs, BEVs' purchase prices are comparable to other vehicle variants when similar additional equipment is considered. Additionally, BEVs are often the variants with the lowest TCO. Diesel ICEVs are almost always the most expensive vehicle variant within a segment.

According to the results obtained within this study, all passenger vehicles cause significant external cost due to environmental damages and partly through governmental financial support. However, in many cases the generated tax revenue can outperform the environmental damages in terms of cost. Since the environmental damages caused by BEVs are the lowest compared to the other energy sources, the full external cost is also the lowest. There is no case within this study where an ICEV causes less external cost than a BEV. FCEVs, although only two vehicles were under consideration, seem to be a good substitute for ICEVs in terms of external cost. However, in terms of TCO, they deliver no significant benefit compared with ICEVs.

Concluding from these results, BEVs offer not only the most reasonable option for buyers in terms of TCO but also for the society in terms of external cost. As expected, the smaller the chosen vehicle is, the lower the TCO will be. Although larger vehicles cause more environmental damages, they cause lower external cost due to the significantly higher generated tax revenue. In order to reduce the financial load on consumers, choosing BEVs over ICEVs can generally be recommended despite the seemingly higher purchase prices.

For commercial vehicle fleets, the results may differ slightly. However, it can be expected that BEVs are still the most sensible option in terms of TCO. Since commercial vehicles usually experience higher usage than private vehicles, BEVs are recommended for vehicle fleets due to their lower mileage-dependent costs and the resulting impacts on TCO. Furthermore, commercial vehicle owners have a special social responsibility and should therefore also consider using vehicles with lower external cost and smaller environmental impacts such as BEVs or FCEVs.

6.2. Outlook

Based on this investigation of TCO and external cost of different available passenger cars, further research can be conducted. One possibility is to extend the list of vehicles under consideration or to perform the same calculations for differently equipped vehicles. This would allow a sensitivity analysis of the assumptions that were made within this paper. Additional results could be obtained by a more detailed prediction of future fuel and electricity prices as well as the determination of real-driving energy or fuel consumption. Especially real-driving scenarios can increase the accuracy of the data related to fuel consumption. The inclusion of this data will enable accurate results for PHEVs, which could then be included into a future study.

Currently, there is an observable trend from conventional ICEVs to BEVs and FCEVs. As of now, the selection of FCEVs is limited to only two vehicles, with hardly any room for equipment changes. BEVs are more common, but mostly offer a very high minimal equipment choice. The selection of more affordable BEVs and FCEVs will likely increase in the future and will therefore improve the TCO and external cost results for these vehicle types as well as the generalizability of all results. Furthermore, new technologies such as multilevel inverters and reconfigurable battery systems will be adopted in BEVs and will potentially reduce vehicle price as well as increase battery lifetime. Another important factor will be bidirectional charging, which can potentially generate income for BEV owners and decrease TCO.

Although this study excludes external costs originating from congestion and accidents, these factors are still present with passenger vehicles. In a future study, these cost components could be calculated for each vehicle segment, since e.g., more expensive vehicles likely lead to higher repair costs after an accident. It is also possible to link the congestion costs e.g., to a certain region in which a vehicle is used. These factors will significantly increase the depth of investigation and therefore should be published in a separate paper.

Future research will take these developments into consideration. Thus, a similar study performed in five to ten years might show different results from the ones obtained within this study. Finally, as the present study is a normative analysis, all real-world behavioral components have been neglected. A future study could integrate descriptive components since actual purchasing behavior of German consumers might differ from purely rational decision making.

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Abbreviations

The following abbreviations are used in this manuscript:

BAFA	Bundesamt für Wirtschaft und Ausfuhrkontrolle
BEV	Battery Electric Vehicle
EoL	End-of-Life
ERP	Enterprise Resource Planning
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LFP	Lithium Iron-Phosphate
NCA	Nickel-Cobalt-Aluminium-Oxide
NMC	Nickel-Manganese-Cobalt-Oxide
PHEV	Plug-in Hybrid Electric Vehicle
SF	Damage-free class (German: 'Schadensfreiheitsklasse')
SoH	State of Health
SUV	Sports Utility Vehicle
TCO	Total Cost of Ownership
VAT	Value Added Tax
VoFI	Visualization of Financial Implications
WLTP	Worldwide Harmonised Light-Duty Vehicles Test Procedure

Appendix A. Vehicles

Table A1. Vehicles under consideration.

Segment	Fuel/Energy	Manufacturer	Model	Variant
A	Gasoline	Volkswagen	up!	1.0
A	Electricity	Volkswagen	up!	e-up!
A	Electricity	smart	fortwo	EQ
B	Gasoline	Opel	Corsa	1.2 DI Turbo
B	Electricity	Opel	Corsa	Electric
B	Gasoline	MINI	Cooper	S 3-door
B	Electricity	MINI	Cooper	SE
C	Gasoline	Volkswagen	Golf	2,0 l TSI OPF DSG
C	Diesel	Volkswagen	Golf	2,0 l TDI SCR DSG
C	Gasoline	Skoda	Octavia	1,5 TSI e-TEC
C	Diesel	Skoda	Octavia	2,0 TDI DSG
C	Electricity	Volkswagen	ID.3	Pro
D	Gasoline	Volkswagen	Passat	2.0 l TSI OPF
D	Diesel	Volkswagen	Passat	2.0 l TDI SCR
D	Electricity	Tesla	Model 3	RWD
E	Gasoline	BMW	5	40i
E	Diesel	BMW	5	40d xDrive
E	Electricity	BMW	i5	eDrive 40
E	Gasoline	Mercedes	E	300
E	Diesel	Mercedes	E	300 d 4MATIC
E	Electricity	Mercedes	EQE	350
E	Hydrogen	Toyota	Mirai	Advanced
F	Gasoline	BMW	8	40i xDrive
F	Diesel	BMW	8	40d xDrive
F	Gasoline	Mercedes	S	450 4MATIC
F	Diesel	Mercedes	S	450 d 4MATIC
F	Electricity	Mercedes	EQS	450 4MATIC
B-SUV	Gasoline	Audi	Q2	35 TFSI S tronic
B-SUV	Diesel	Audi	Q2	35 TDI S tronic
B-SUV	Gasoline	Hyundai	Kona	1.6 GDI DCT
B-SUV	Diesel	Hyundai	Kona	1.6 CRDi DCT
B-SUV	Electricity	Hyundai	Kona	Elektro
C-SUV	Gasoline	Opel	Mokka	1.2 DI Turbo
C-SUV	Diesel	Opel	Mokka	1.5 Diesel
C-SUV	Electricity	Opel	Mokka	e
C-SUV	Gasoline	Mercedes-Benz	GLA	200
C-SUV	Diesel	Mercedes-Benz	GLA	200 d
C-SUV	Electricity	Mercedes-Benz	EQA	250
D-SUV	Gasoline	Hyundai	Tucson	1.6 T-GDI DCT
D-SUV	Diesel	Hyundai	Tucson	1.6 CRDi DCT
D-SUV	Electricity	Hyundai	IONIQ 5	Elektro 58 kWh
D-SUV	Hydrogen	Hyundai	Nexo	Hydrogen
D-SUV	Gasoline	Volkswagen	Tiguan	2.0 TSI OPF DSG
D-SUV	Diesel	Volkswagen	Tiguan	2.0 TDI SCR DSG
D-SUV	Electricity	Volkswagen	ID.4	Pro Performance
D-SUV	Electricity	Tesla	Model Y	RWD
E-SUV	Gasoline	Mercedes-Benz	GLE	450 4MATIC
E-SUV	Diesel	Mercedes-Benz	GLE	450 d 4MATIC
E-SUV	Electricity	Mercedes-Benz	EQE	500 4MATIC
F-SUV	Gasoline	Audi	Q8	55 TFSI quattro
F-SUV	Diesel	Audi	Q8	50 TDI quattro
F-SUV	Electricity	Audi	Q8	50 e-tron quattro
M	Gasoline	Citroën	Berlingo	PureTech 110 S&S
M	Diesel	Citroën	Berlingo	BlueHDi 100 S&S
M	Electricity	Citroën	Berlingo	e

Appendix B. Cost Components for All Vehicle Segments

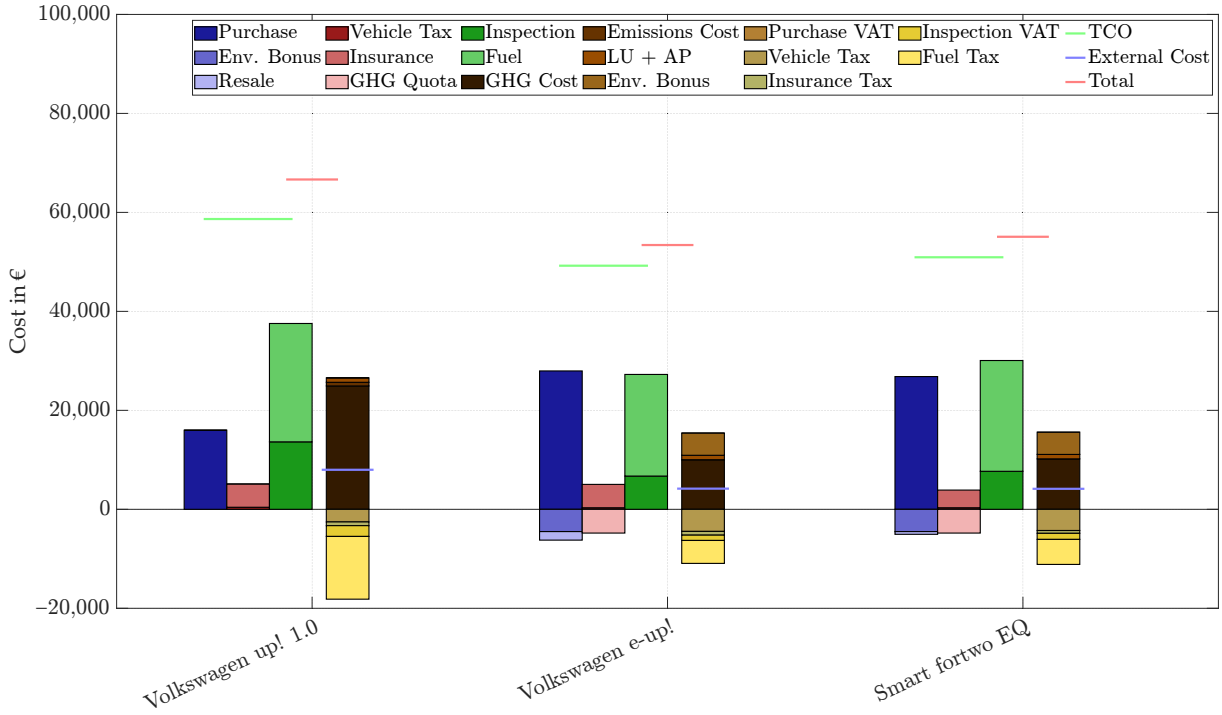

Figure A1. Cost components for vehicles in the A segment.

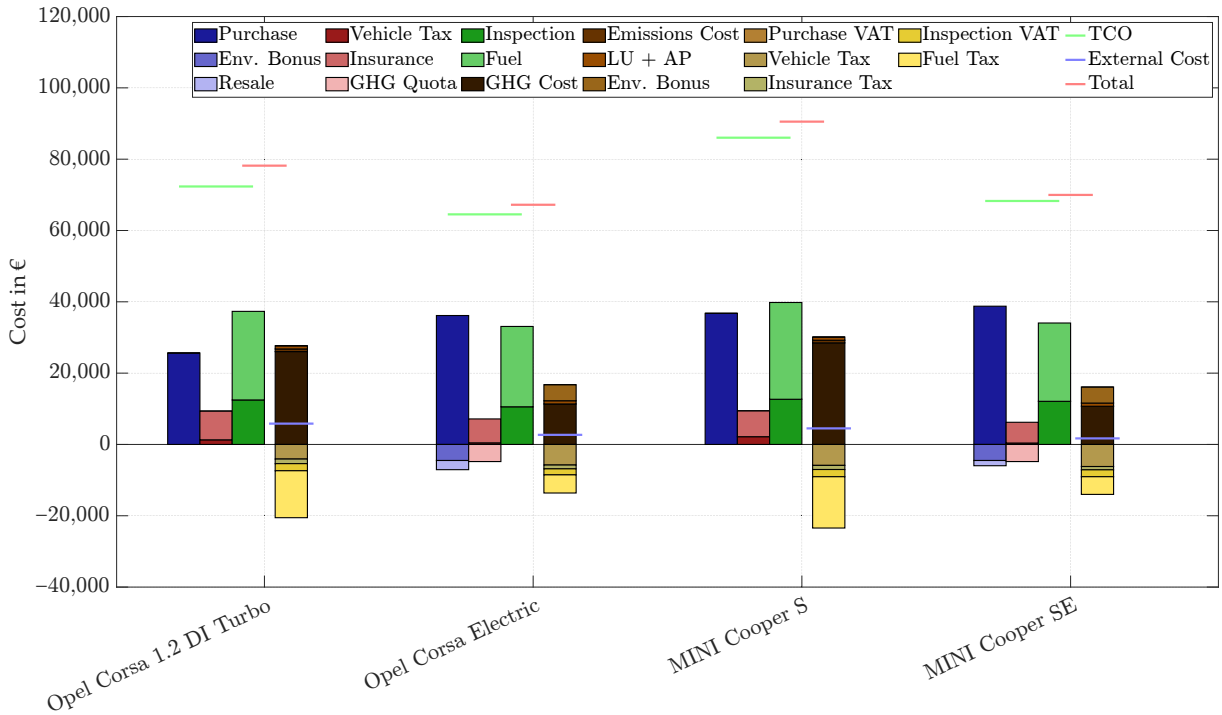

Figure A2. Cost components for vehicles in the B segment.

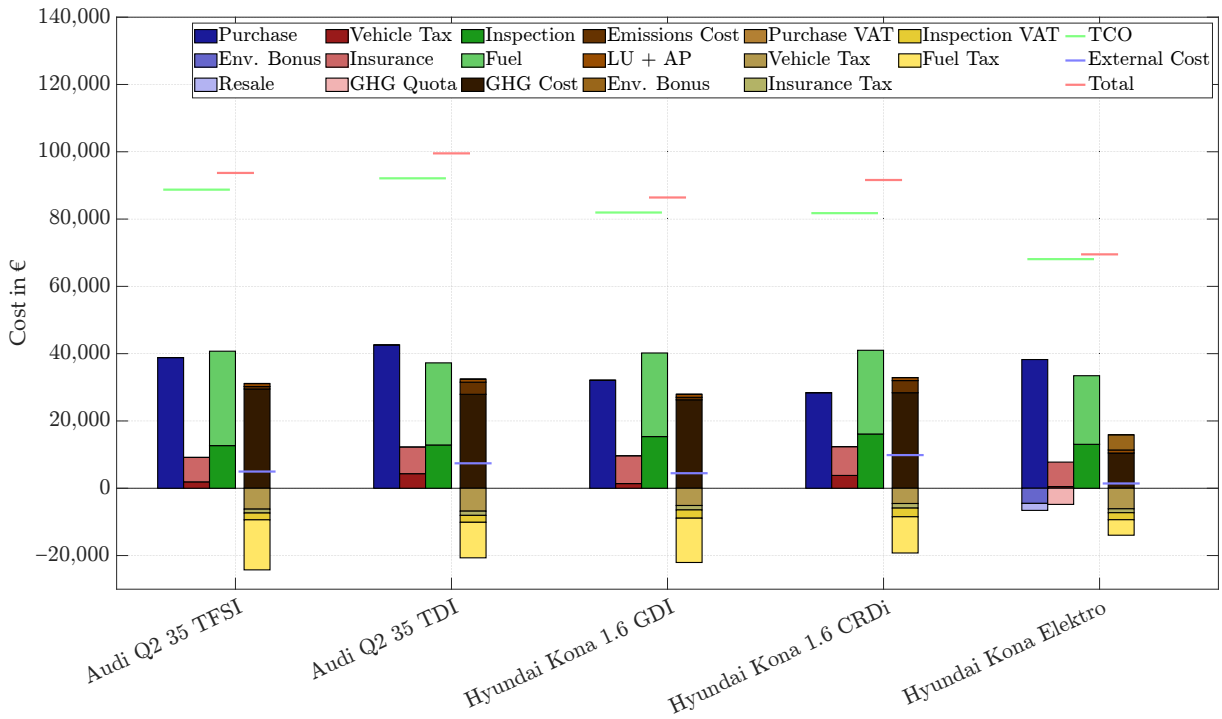

Figure A3. Cost components for vehicles in the B-SUV segment.

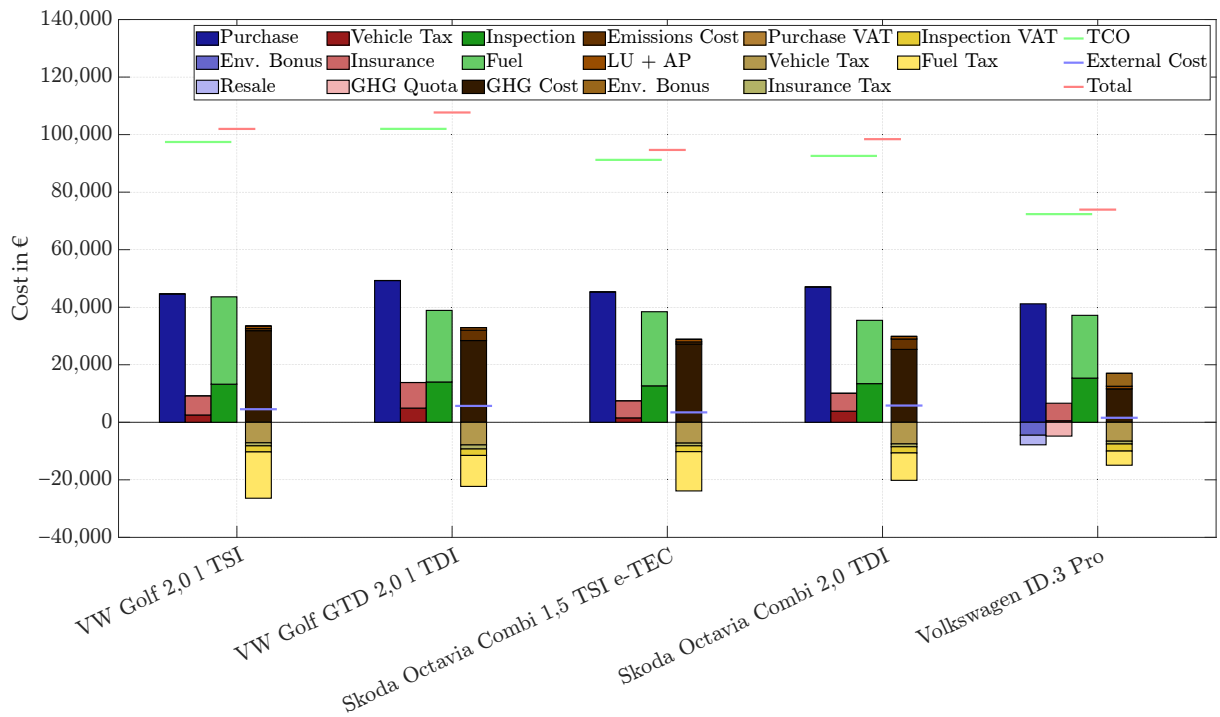

Figure A4. Cost components for vehicles in the C segment.

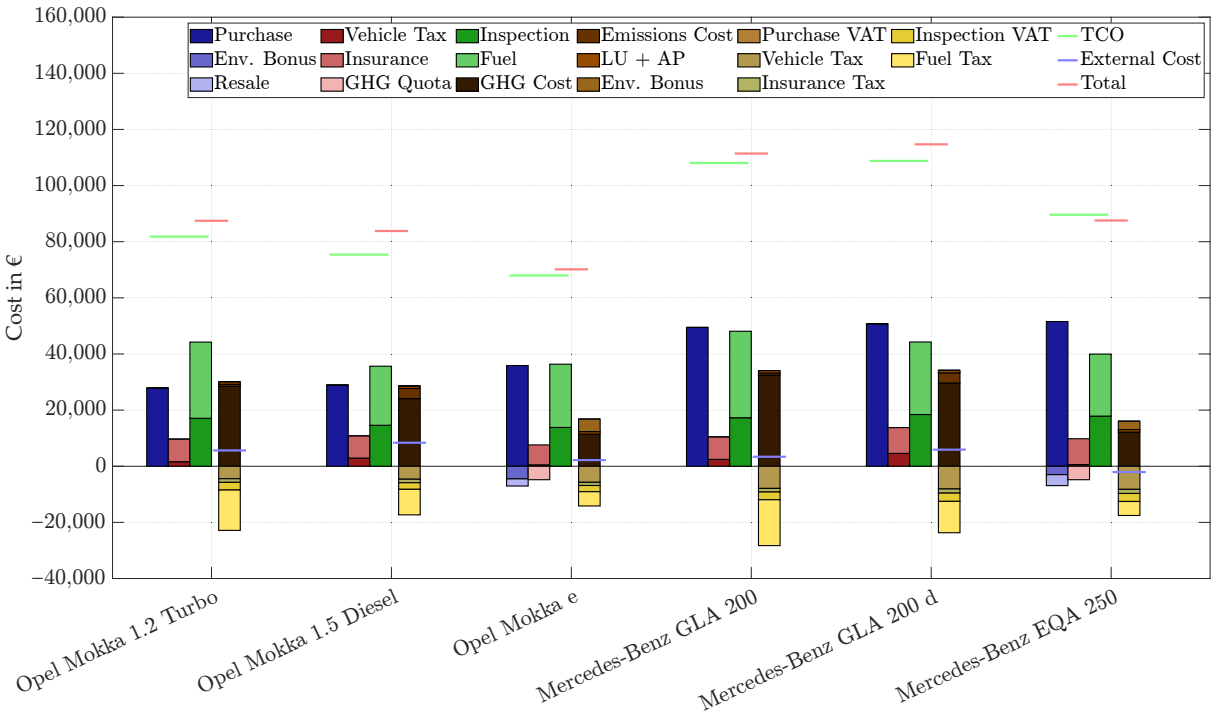

Figure A5. Cost components for vehicles in the C-SUV segment.

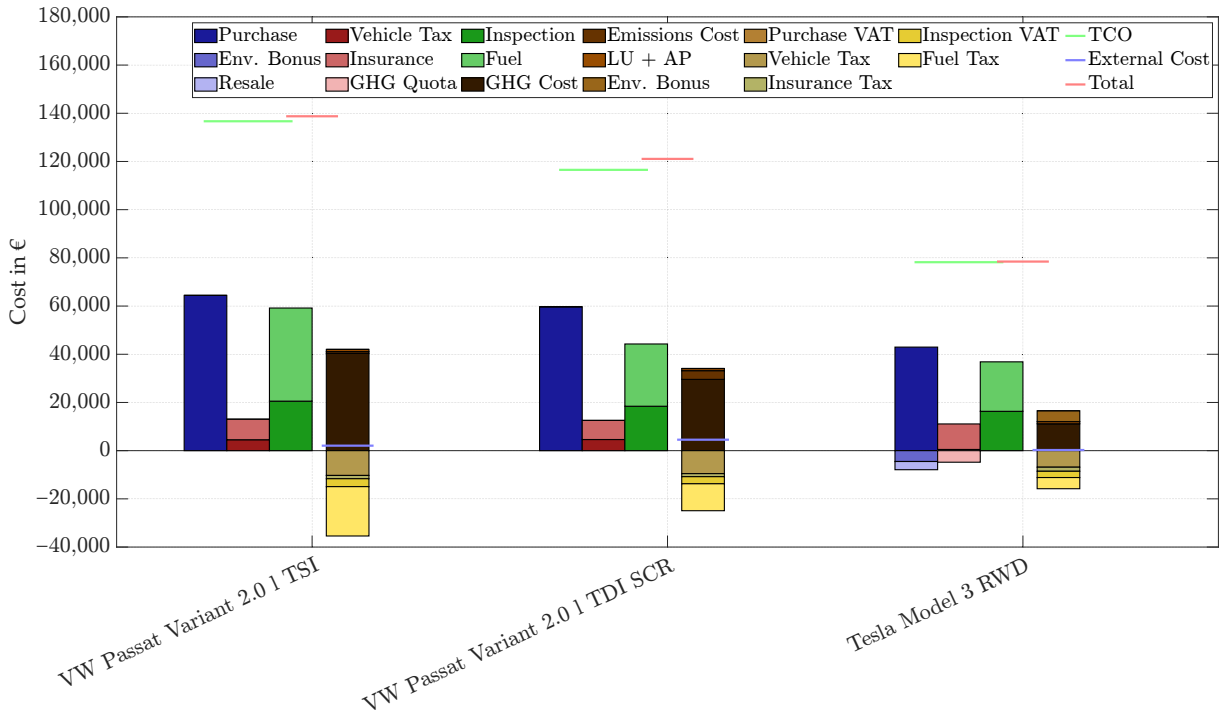

Figure A6. Cost components for vehicles in the D segment.

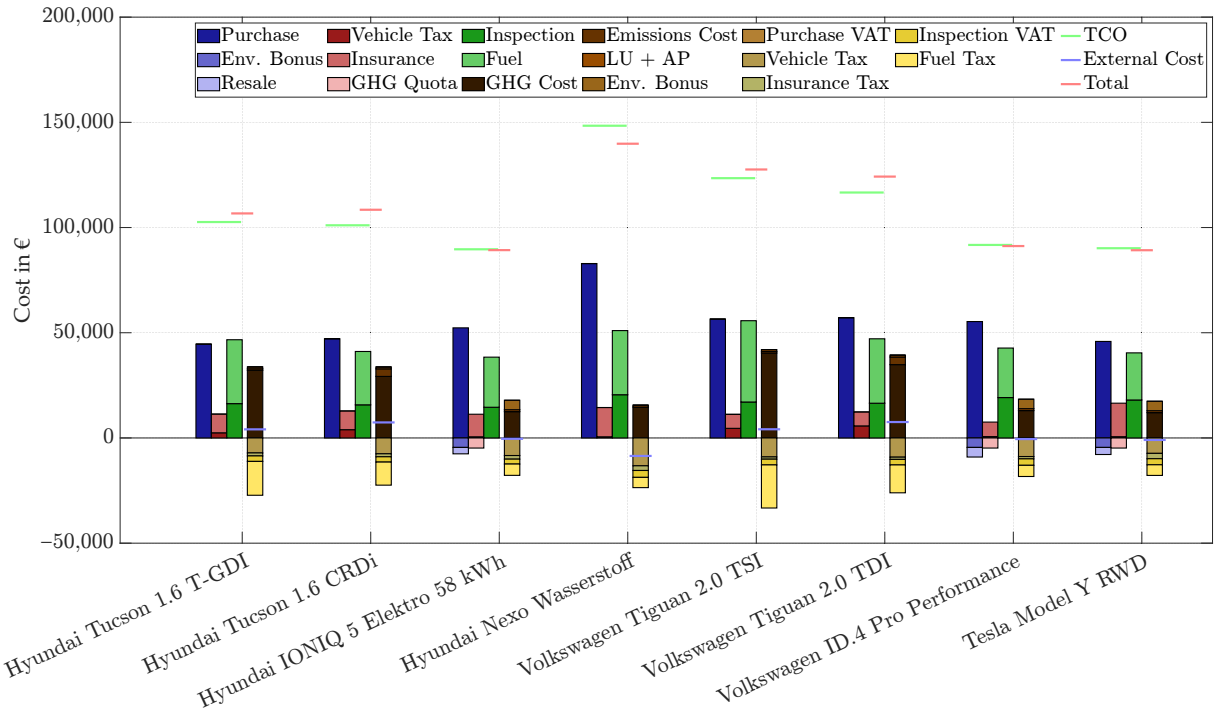

Figure A7. Cost components for vehicles in the D-SUV segment.

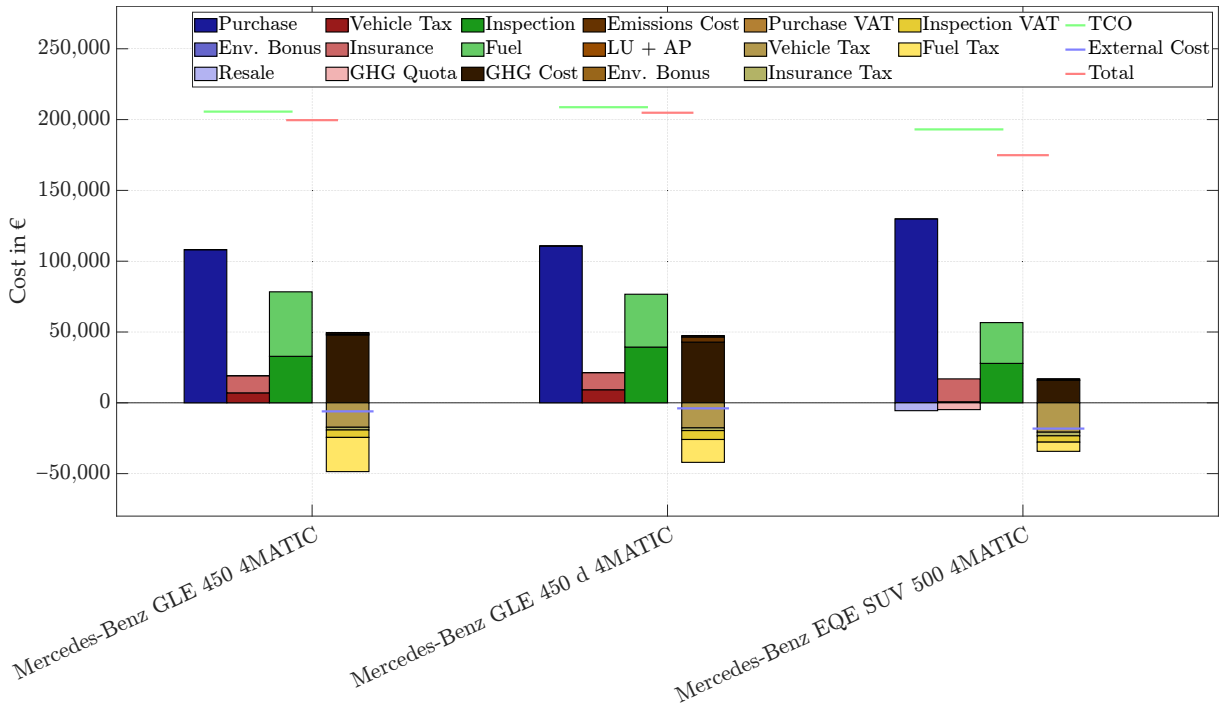

Figure A8. Cost components for vehicles in the E-SUV segment.

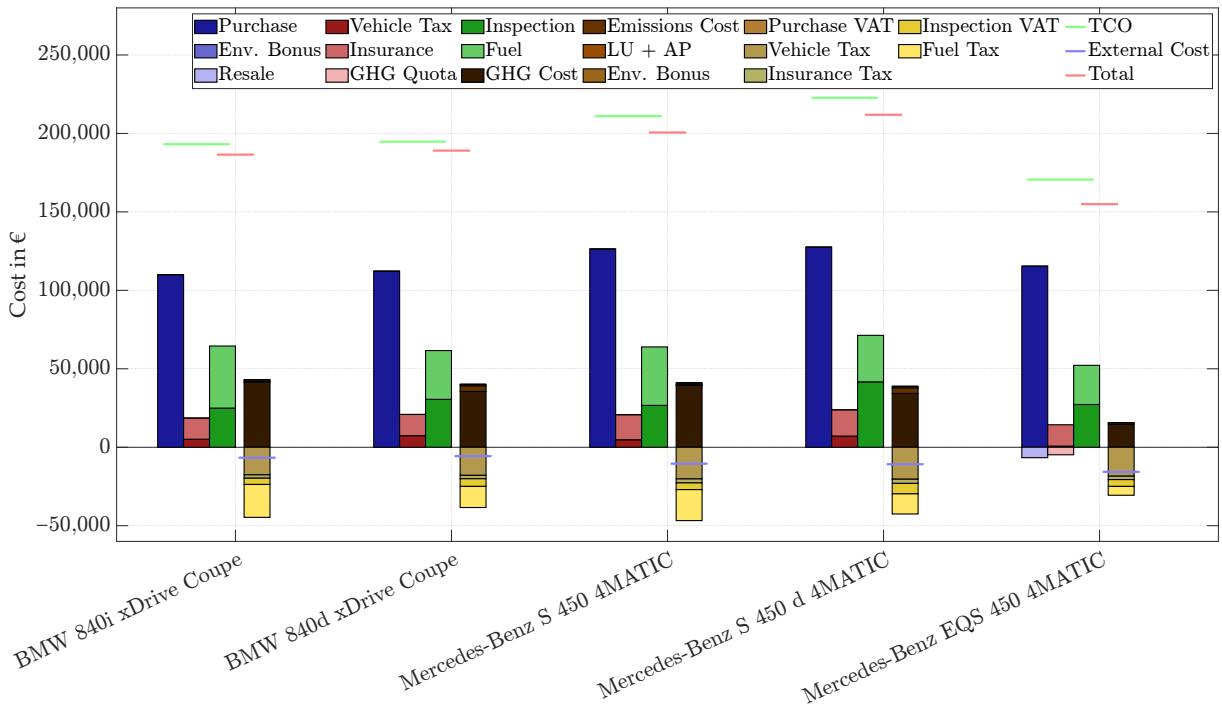

Figure A9. Cost components for vehicles in the F segment.

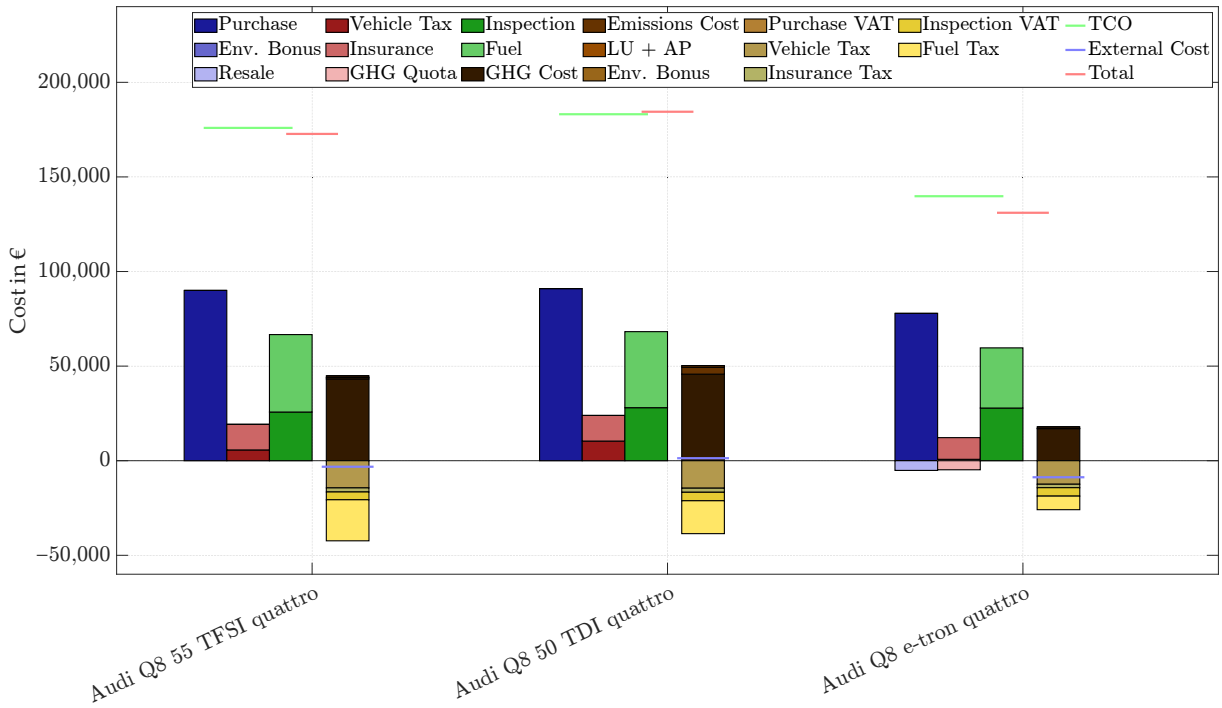

Figure A10. Cost components for vehicles in the F-SUV segment.

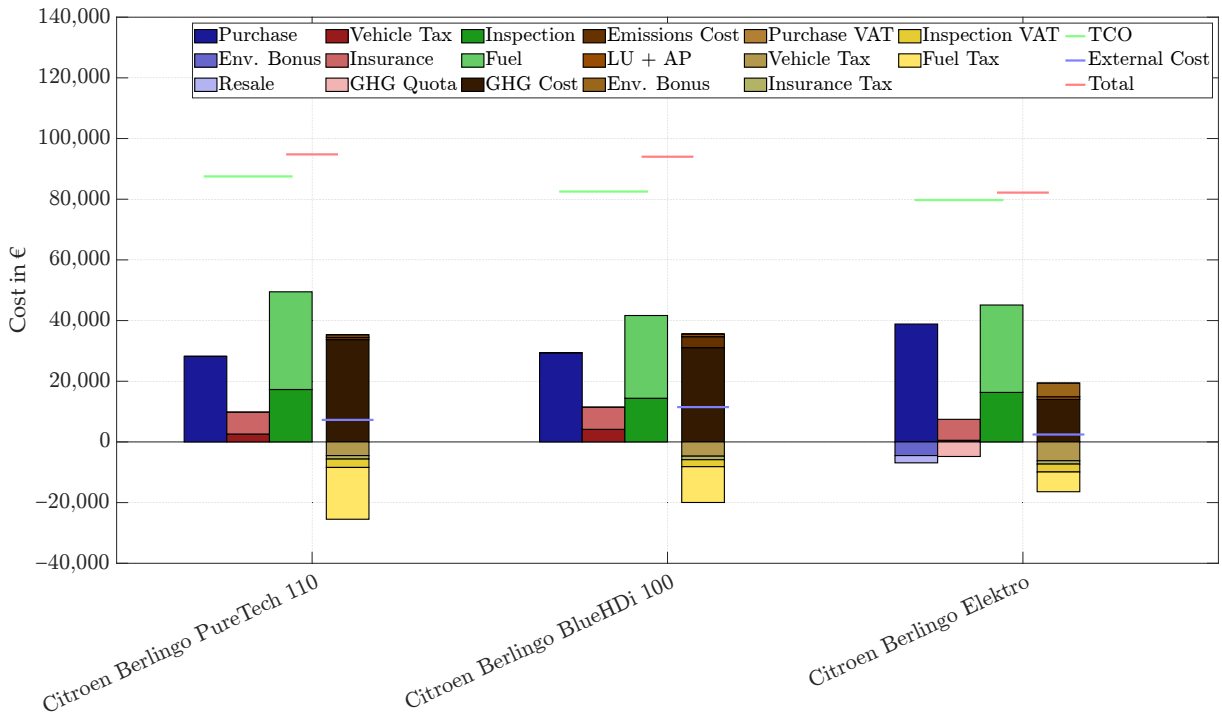

Figure A11. Cost components for vehicles in the M segment.

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