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Future projections of Germany's car fleet - Development of a stock-flow cohort model under CO_2 performance standards and effects on annual fleet composition, energy demand and emissions

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1. Introduction

The transportation sector is a significant contributor to global greenhouse gas (GHG) emissions, accounting for 16 % of total GHG emissions, with road transport alone responsible for 11 % of the overall GHG emissions (Statista: Transportation emissions worldwide, 2025). Passenger cars and vans consume ca. 25 % of the global fossil fuel supply and contribute around 10 % to global energy-related emissions (IEA, 2023). EU-wide transport accounts for ca. 25 % of total European GHG emissions, with passenger cars responsible for 60 % of these transport-related emissions (EEA: Transport and Mobility, 2025). In Germany, the transport sector emitted 142 million tons (Mt) of CO_2 in 2022, with cars alone contributing with 89 Mt (62 %), while heavy-duty vehicles accounted for 40 Mt (Supplementary Figs. 2 and 3). This makes road transport a key focus area for national decarbonization efforts, as it represents ca. 11 % of Germany's total CO_2 emissions (Statista: Greenhouse gas emissions in, 2024).

The EU has implemented stringent climate policies to align with the Paris Agreement (UNFCCC, 2015), including the EU Green Deal (European Commission, 2019), EU Fit for 55 package (European Commission, 2021) and national initiatives such as Germany's Climate Protection Act (Bundesregierung: Ein Plan fürs Klima, 2024; BMWK: Klimaschutzgesetz, 2022). These regulations establish legally binding sector-specific environmental policies, including CO_2 performance standards (EUR-LEX:, 2024), resulting in Germany's 2030 goal to achieve 15 million battery electric vehicles (BEVs) (Bundestag: 15 Millionen E, 2024). From 2035 onwards, the EU has effectively mandated a phase-out of new internal combustion engine (ICE) cars by requiring that the average tailpipe emissions of new passenger cars and vans reach zero (EUR-LEX:, 2024; EUR-LEX:, 2023; European Commission, 2024a). Since fossil fuels cannot meet this requirement, ICEs would only remain viable if operated exclusively with renewable fuels of non-biological origin. In this sense, the regulation effectively functions as an indirect ban on new ICE registrations. Given that the road transport sector is among the most regulated within the EU (Schulthoff et al., 2022), the effectiveness of these CO_2 performance standards in achieving climate goals remains a subject of analysis. GHG emissions from the transport sector can be mitigated through three fundamental approaches: efficiency improvements, technological substitutions, and demand-side solutions (Schulthoff et al., 2022; Winkler et al., 2023). This study focuses on the first two options while assuming a similar individual mobility demand.

Therefore, this paper examines the future development of the German car fleet and its impact on final energy demand and CO_2 emissions over time. Specifically, it assesses whether current CO_2 performance standards are sufficient to meet climate targets and evaluates the alignment of Germany's transport policies with net-zero goals. It also investigates the implications of the EU's 2035 combustion engine ban. Furthermore, it explores the impact of past regulatory decisions on fleet evolution and potential decarbonization trajectories.

Several studies have analyzed vehicle-fleet developments in Germany, with particular influence from five major energy-system studies (BCG, 2021; Dena: dena, 2021; Gnann et al., 2024a; Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021). However, key limitations persist. These studies lack sufficient information about their underlying assumptions and chosen methodology, which hinders the ability to reproduce the results. In addition, many other studies address aspects of this topic; however, in most cases, critical assumptions, especially dynamic models, are embedded within complex calculations, reducing interpretability (Revany et al., 2021; Chatterjee et al., 2022). Few studies fully disclose data sources and modeling frameworks, restricting policy applicability (Winkler et al., 2023; Gnann et al., 2022; Trost et al., 2017). But transparent and accessible fleet models are essential to improve the understanding of fleet evolution and to ensure that policies are effectively aligned with EU climate targets.

To address these limitations, this study incorporates a comprehensive fleet modeling framework for various propulsion technologies, including internal combustion engine vehicles powered by diesel, petrol,

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compressed natural gas (CNG), and liquefied petroleum gas (LPG). Hybrid vehicles, including hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV), are also considered, with petrol or diesel powertrains. BEVs and fuel cell electric vehicles (FCEV) are fully electric alternatives, with BEVs relying on rechargeable batteries and FCEVs generating electricity via hydrogen-powered fuel cells.

This study contributes to both methodological transparency and policy impact analysis by introducing Fleet Development Forecast (FLEETCAST), an open-source vehicle stock model that simulates fleet evolution under various policy scenarios and integrates historical vehicle data from the German Federal Motor Transport Authority (KBA) (Kraftfahrt-Bundesamt, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h, 2023), improving transparency of results and replicability. Further, it provides fleet evolution projections by analyzing the long-term development of the German car fleet under different adoption scenarios. It evaluates the impact of CO_2 performance standards on fleet development, energy consumption, and emissions reductions. Also, it assesses whether CO_2 performance standards are sufficient to meet EU and national climate targets and investigates the effects of potential policy changes, including the 2035 combustion engine ban and adjustments to CO_2 performance standards.

2. Background

Below, the regulatory framework applicable to Germany is outlined, followed by a brief overview of energy-system studies to enable subsequent comparison.

2.1. Regulatory framework

The impending indirect new registration prohibition of ICE vehicles and the implementation of stringent CO_2 performance standards are central factors shaping consumer purchasing behavior and influencing the trajectory of the automotive industry across Europe (EUR-LEX:, 2024; EUR-LEX:, 2023). While discussions surrounding the potential inclusion of e-fuels persist (Regulation (EU) 2023/851 §11 (European Union, 2023)), their availability is negligible as of 2025, and projections suggest that their role in road transport will remain constrained due to existing production limitations and the given economic constraints. Instead, synthesized hydrocarbons are expected to be primarily utilized in sectors such as aviation and maritime shipping, where economic incentives and binding quotas create a potentially higher willingness to adopt these fuels (Neuling and Berks, 2023; European Commission, 2024b). While the role of e-fuels in passenger road transport remains under discussion, studies indicate that their long-term impact will be marginal due to production scalability challenges and economic risks (Neuling and Berks, 2023). As a result, most regulatory and industrial efforts are directed toward BEV adoption, with FCEVs maintaining a more limited presence in the market (European Commission, 2024a).

BEVs are emerging as the dominant technology among OEMs, while comparatively fewer manufacturers are also pursuing FCEVs (Statista: Anzahl angebotener Elektroauto, 2025). This shift aligns with the EU's decarbonization strategy, which foresees a steady decline in new registrations of ICE vehicles, including HEVs and PHEVs, culminating in a complete phase-out by 2035 under progressively tightening CO_2 performance standards ((EU)2019/631 (EUR-LEX:, 2024), and (EU) 2023/1623 (EUR-LEX:, 2023)). Concurrently, Germany has set ambitious national targets to have at least 15M BEVs on its roads by 2030 and achieve complete climate neutrality by 2045 (BMWK: Klimaschutzgesetz, 2022; Bundestag: 15 Millionen E, 2024). These measures reinforce broader EU climate objectives, aiming to accelerate the adoption of BEVs, expand charging infrastructure, and encourage both industrial stakeholders and consumers to transition toward zero-emission mobility.

2.2. Decarbonization pathway studies

A key feature of these five major energy system studies (Table 1) is their fleet development assessment and energy demand and emissions projections. Some explicitly model final energy demand for cars, while others primarily focus on sector-wide transformations. Although these studies serve as important reference points for policymakers, they frequently rely on proprietary software, restricting reproducibility and independent validation.

The reviewed studies collectively identify electrification being essential for achieving Germany's 2045 carbon neutrality goal, significantly reducing oil import dependency. Besides the ramp-up of BEVs, FCEVs may begin to emerge in the mid-2030s but remain marginal due to higher vehicle and fuel costs. Increased electrification substantially elevates grid loads, necessitating infrastructure upgrades. Decarbonizing electricity generation further enhances CO_2 savings within the transport sector, highlighting the need for integrated, cross-sectoral planning (BCG, 2021; Dena: dena, 2021; Gnann et al., 2024a; Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021). The studies further indicate that accelerated electrification is not only cost-effective but also offers significant industrial opportunities. By 2030, battery-electric vehicles (BEVs) become economically favorable compared to internal combustion engine vehicles (ICEs) for nearly all consumers due to lower energy and maintenance costs, with BEVs achieving an annual market volume of ca. €80 billion in Germany (Ariadne and Kopernikus-Projekt, 2025). Hydrogen fuel cell electric vehicles (FCEVs), however, only gain traction under highly favorable conditions – low hydrogen prices, reduced vehicle costs, and targeted infrastructure development – while plug-in hybrids (PHEVs) generally remain a transitional technology unless prolonged by policy or market constraints (Ariadne and Kopernikus-Projekt, 2025).

But it is also highlighted that electrification alone may be insufficient to meet climate targets due to slow adoption rates, fleet turnover limitations, and continued liquid fuel demand from remaining ICE vehicles (Milovanoff et al., 2020; Striepe et al., 2024). Studies analyzing electric vehicle (EV) diffusion in Germany have identified market penetration and policy integration as key challenges, emphasizing the need for systemic changes beyond vehicle electrification (Cao Van et al., 2023). Additionally, recent work has explored vehicle lifespan capping as a mitigation strategy but found it neither cost-effective nor sufficient for

Table 1
Overview of investigated energy system studies in Germany.

Year	Scope	Assessment of Road Transport	Reference
2021	National decarbonization pathways	Analyzes fleet electrification, fuel alternatives, and policy-driven adoption scenarios.	BCG (2021)
2021	Energy transition across sectors	Examines infrastructure requirements for BEVs and FCEVs with detailed fleet stock projections.	Dena: dena (2021)
2024	Decarbonization scenarios for road transport	Analyzes alternative fuel technologies, focusing on electricity, hydrogen, synthetic methane, and liquid synthetic fuels.	Gnann et al. (2024a)
2021	Climate neutrality strategies	Evaluates electrification, hydrogen, and synthetic fuel roles in achieving net-zero transport emissions.	Ariadne and Kopernikus-Projekt (2021)
2021	CO_2 reduction strategies across sectors	Assesses vehicle stock development, energy demand scenarios, and emissions reduction pathways.	Klimaneutralität et al. (2021)

substantial emissions reductions (Striepe et al., 2024). Other studies claim that a rapid and large-scale reduction in car use is necessary to meet short-term emission targets, adhere to stringent carbon budgets, and reduce the demand for additional technology, materials, and minerals. Most emissions within the remaining carbon budget originate from vehicles already in operation, making accelerated ICE vehicle scrappage or an earlier ban on fossil fuel potential policy options to reduce residual emissions. Further, research claims that effective policy measures should focus on retrofitting existing vehicles with electric engines and reducing vehicle distance driven (Winkler et al., 2023). Besides that, studies show that a sufficiently high CO_2 tax is required, set at around 150 €/t CO_2 in 2030, to significantly accelerate EV adoption, leading to up to 17M additional EVs by 2050 (Cao Van et al., 2023). Fleet and company cars are expected to drive early adoption, while private customers will follow as the relative costs of conventional vehicles increase. Even without a CO_2 tax, the German government's 2030 EV stock target of 7M–10M can be met if purchase premiums remain and cost reductions for EVs continue. However, further policy efforts should consider a flexible CO_2 tax trajectory accounting for energy costs, user behavior, and vehicle availability (Cao Van et al., 2023). Overall, studies underline that CO_2 taxation is an effective measure to drive the adoption of innovative powertrains and alternative fuels (Trost et al., 2017). Internal combustion engines will remain dominant in the short to medium term due to efficiency improvements and increased adoption of compressed natural gas vehicles. Hybrid powertrains with external charging (PHEVs) are expected to lead EV adoption until 2030, particularly for larger and light commercial vehicles. In the long term, BEVs will dominate new vehicle registrations as battery costs decline.

Some studies have projected that very high carbon prices (e.g., >400 €/t) could accelerate EV penetration rates substantially (Trost et al., 2017). However, such assumptions should be considered illustrative, as the political feasibility of sustained carbon prices at this level is highly uncertain. In practice, factors such as declining EV costs and the expansion of charging infrastructure are likely to play a more central role in shaping future adoption. Further, final energy demand could decline by up to 60 %, while CO_2 emissions may be reduced by 84–92 % compared to 2013 levels. Synthetic gaseous fuels (power-to-gas) offer a viable solution to displace fossil fuels in cases where full electrification is not feasible.

3. Approach and method

This section introduces the overall approach and mathematical formulation used in the model to address the research question of the future development of Germany's car sector. The model employs a bottom-up approach, integrating diffusion modeling, fleet turnover, and a stock cohort flow methodology to analyze vehicle fleet composition and its environmental impact over time. The framework incorporates established formulations from fleet diffusion and urban mobility models (Winkler et al., 2023; Gnann et al., 2024a; Trost et al., 2017; Cao Van et al., 2023; Naumov et al., 2023). The diffusion modeling component captures how new technologies spread throughout the fleet, while fleet turnover represents replacing or decommissioning older vehicles. The stock cohort flow method tracks vehicle cohorts over time, providing insights into technological transitions and aging vehicle effects. The model is deterministic, requiring specific data inputs such as survival rates, decommissioning rates by age, and newly registered vehicles by technology. These factors determine whether vehicles remain

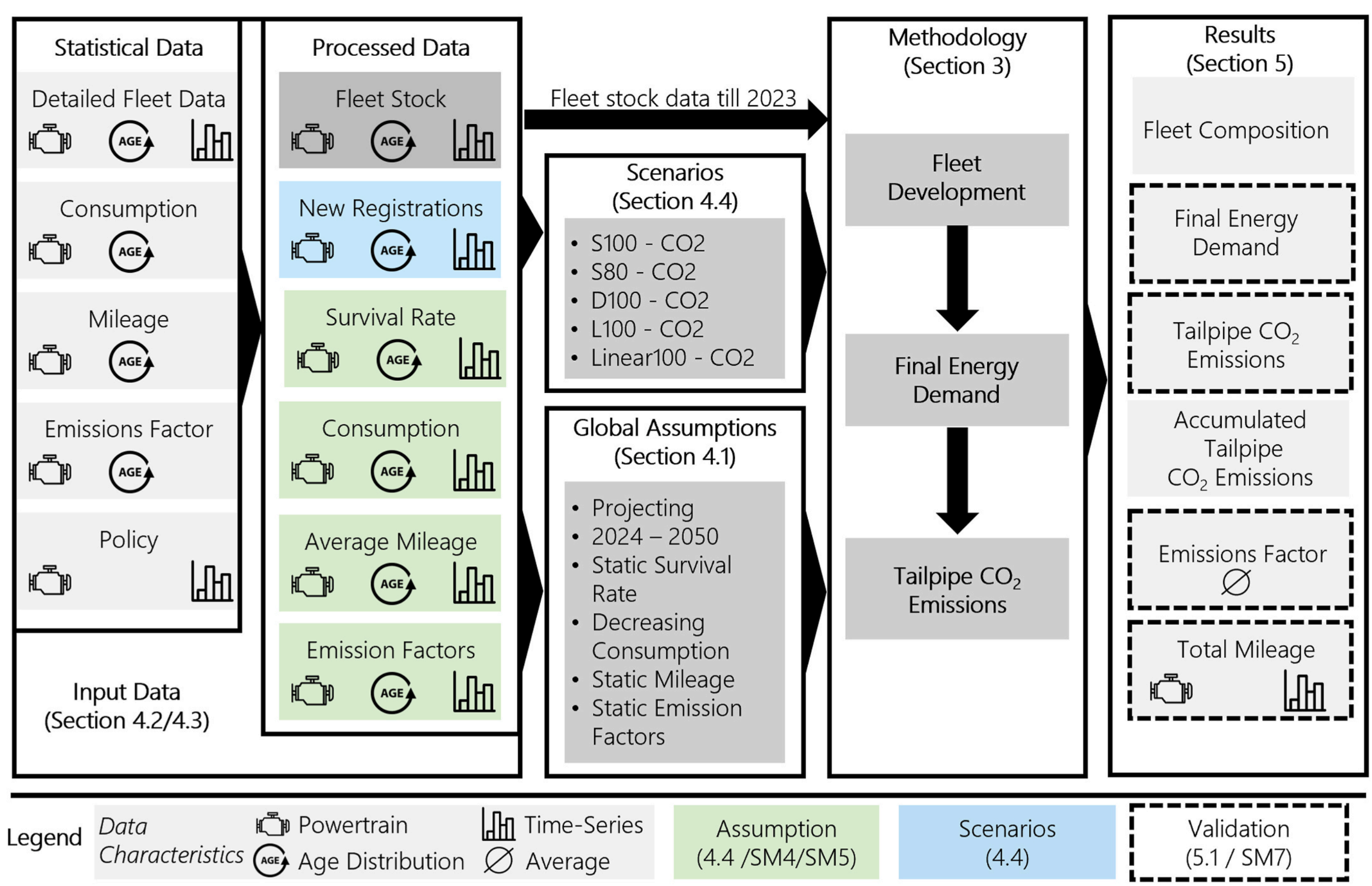

Fig. 1. Overview of the study approach, illustrating the integration of input data, methodological processes, and scenario-based projections leading to fleet composition, energy demand, and emissions outcomes. The model follows a structured stock-flow framework, incorporating vehicle registrations, survival rates, and policy assumptions to simulate the evolution of the German car fleet.

operational or exit the fleet, with the stock categorized by powertrain, age, and technology. The primary exogenous inputs are the number of newly registered vehicles by technology, defined under different scenarios to explore policy and market dynamics.

Fig. 1 illustrates the overall approach, detailing the interaction between input data, methodological processing, and scenario-based projections leading to the results. The model follows a structured data-driven approach, focusing on fleet evolution, energy demand, and emissions modeling. The methodology consists of the following key components:

- Input Data. The model integrates statistical and processed data sources (Sections 4.2 and 4.3; supplementary 3–4), as well as additional processed data relevant to scenario development (Section 4.4; supplementary 4–5). This includes vehicle stock data, fuel consumption trends, distance-driven statistics, and emissions factors.
- Global Assumptions and Scenario Definition. The approach incorporates predefined assumptions regarding fleet survival rates, vehicle efficiency improvements, and policy measures (Section 4.1). The scenario definitions (Section 4.4) establish distinct pathways for evaluating the impact of different regulatory and technological developments on fleet composition and emissions.
- Fleet Modeling Methodology. The model's core simulates fleet stock evolution, energy demand, and tailpipe CO_2 emissions based on input data and scenario assumptions (Section 3).
- Results and Outputs. The methodology produces estimates of fleet composition, final energy demand, and tailpipe CO_2 emissions (Section 5). Additionally, accumulated CO_2 emissions and total distance-driven calculations provide insights into long-term emission trends under different scenarios.

The model is configured for a tank-to-wheel (TTW) CO_2 emissions analysis (Sections 2.1 and 4.1), aligning with current European CO_2 accounting policies.

3.1. Fleet development

The fleet development is modeled using a stock–cohort flow approach, which allows for a detailed analysis of the composition and evolution of the vehicle fleet over time. Symbols and indices used throughout this section are summarized in Table 2.

The development of the fleet is then described by Eqs. (3)–(1):

$$S_t = \sum_T S_{T,t} = \sum_a \left(S_{T,a,t-1}\, s_{T,a}\right) + N_{T,t} \quad \text{with } N_{T,t} = N_{Total,t}\, r_{T,t} \qquad \text{Eq. (3-1)}$$

The stock in year t, S_t is derived from vehicles surviving from the previous year, adjusted by their respective survival rates $s_{T,a}$ and the newly registered vehicles $N_{T,t}$. New registrations are calculated by multiplying the total number of new vehicles $N_{Total,t}$ by the technology-specific market share $r_{T,t}$, which is defined exogenously in each scenario. This structure allows the model to account for both the age distribution of the fleet (a) and the technology mix (T).

Table 2
Definitions of symbols and indices.

Symbol	Meaning	Symbol/ Indices	Meaning
S_t	Stock in year t	E	Final energy demand
N	Newly registered vehicles by technology	M	Annual distance driven
s	Survival rate	c	Fuel consumption
R	Share of new registrations by technology	t	Year
T	Technology/powertrain	a	Age
e	Emission factor	k	Registration year
C	Carbon Emissions		

The fleet development model uses fixed registration shares rather than a dynamic economic equilibrium approach. As a result, it does not capture price-driven consumer behavior, which limits its sensitivity to market conditions and policy incentives. Vehicle decommissioning is modeled independently of new registrations, without a feedback mechanism to balance the total vehicle count. While a dynamic equilibrium approach could improve realism by incorporating such interactions, it would require complex and highly uncertain assumptions about consumer behavior and macroeconomic cycles, which are beyond the scope of this study.

3.2. Final energy demand and tailpipe CO_2 emissions

The fleet's final energy demand E is obtained by aggregating across technologies, ages, and years, as shown in Eqs. (3)–(2).

$$E = \sum_t E_t \quad \text{with } E_t = \sum_T \sum_a S_{T,t,a}\, M_{T,a}\, c_{T,t-a} \text{ with } (k = t - a) \qquad \text{Eq. (3-2)}$$

$S_{T,t,a}$ denotes the stock of vehicles of technology T in year t and age a ; $M_{T,a}$ is the annual distance driven; and $c_{T,k}$ is the specific fuel or energy consumption of registration cohort k. The formulation links each vehicle age to its registration cohort via $= t - a$, ensuring that cohort-specific consumption values are applied correctly.

Tailpipe CO_2 emissions C in year t are then given in Eqs. (3)–(3), where $e_{T,t}$ denotes the technology-specific emission factor.

$$C_t = \sum_T e_{T,t}\, E_{T,t} \qquad \text{Eq. (3-3)}$$

4. Frame conditions, data and scenario definition

4.1. Global Assumptions

The following section details the overarching methodological assumptions applied to model the German car market from 2024 to 2050 based on historical trends and recent data (2014–2023). These assumptions establish the foundation for scenario projections, ensuring clarity, reproducibility, and interpretability of results:

4.2. Methodological framework

Below important aspects of the methodological framework are outlined.

- The study focuses explicitly on the German car market, with simulations covering 2024 to 2050. Historical statistical data between 2014 and 2023 form the basis of trends. The situation in the year 2020 is included in visualizations as a reference year for actual statistical data.
- Simulations commence in, 2024, relying on historical new registration and vehicle inventory data. Scenarios differ primarily by varying the technology-specific new registration rates between 2024 and 2035 (Section 4.4) (for additional interactive scenarios see supplementary GitHub repository (Github, 2025)).
- Vehicle distance-driven patterns and vehicle survival rates are treated as static variables due to data availability constraints (Section 4.3).
- Fleet development primarily depends on two core variables; these are the new vehicle registrations (treated as an exogenous input, fixed at an annual average of 3.1M vehicles, reflecting the historical average from 2014 to 2023) and the vehicle survival (decommissioning rates).
- The survival rate was empirically developed for the entire fleet, reflecting all technologies and also separately for specific

technologies (e.g., Petrol ICE). Due to insufficient data availability, the empirical fleet average is used.

The specific parameters utilized for emissions calculations, consumption data, and assumptions on vehicle characteristics are summarized in Table 3 (for further methodological details see supplementary 4).

The PHEV electric-driving share was fixed at 10 %, based on empirical studies of current usage behavior (Fraunhofer, 2022). This value represents a conservative lower-bound estimate. In practice, the share may increase as infrastructure expands, and PHEVs move from company fleets to private ownership.

4.3. Statistical database

The primary data source is the micro-dataset on vehicle inventory provided by the German Federal Motor Transport Authority (KBA), including information on the total vehicle fleet, new registrations, and decommissioning records in Germany from 2014 to 2023. Covering ca. 62M vehicles annually, these data offer detailed insights into recent fleet composition trends and developments (Kraftfahrt-Bundesamt, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h, 2023). Additionally, the approach integrates supplementary official registration reports published by the German Federal Motor Transport Authority (KBA), in particular the *Fahrzeugzulassungen* series (FZ14, FZ28), to close data gaps in the analysis of fleet characteristics and historical shifts in propulsion technologies. (see data availability GitHub repository (Github, 2025)). The available KBA data extends back to 2014 being insufficient for deriving detailed technology- or vehicle-type-specific survival rates (e.g., differentiating petrol vs. diesel vehicles or SUVs vs. sedans).

Table 3
Summary of key parameters and assumptions underlying the fleet model, including emission calculations, vehicle usage patterns, and data preprocessing.

Parameter	Assumption	Reference
CO_2 Tailpipe Emissions	Tailpipe emissions from internal combustion engine vehicles are accounted for in the transport sector, while emissions from electricity generation are assigned to the energy sector.	Bundesamt für Justiz (2024)
CO_2 Electricity Emissions	Emissions from electricity generation are covered under the European Emissions Trading Scheme (ETS I). The emissions factor for electricity is set to zero in the transport model since these emissions are already accounted for in the energy sector.	Bundesamt für Justiz (2024)
PHEV Electricity Share	The share of electric driving for PHEV is assumed to be constant at 10 %, based on the average value reported in the Fraunhofer Study for company cars.	Fraunhofer (2022)
Emission Factors	Petrol: 2.37 kg CO_2 per liter; Diesel: 2.65 kg CO_2 per liter, Electricity: 0–0.4 kg/kWh (CO_2 scenarios) (supplementary 4.3, 4.4)	(Wissenschaftlicher Dienst des Bundestags, 2019; BAFA, 2023; BMF, 2024; Knörr, 2022)
Oldtimers Survival	Approximately 0.3 % of vehicles are assumed to enter the “Oldtimer phase,” with an estimated annual distance driven of 500 km.	Data Analysis & preprocessing based on (Kraftfahrt-Bundesamt, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h, 2023)
Consumption Data	Fuel consumption data is compiled from multiple sources and preprocessed to create an annual resolution suitable for the model.	(EWI, 2019; KBA, 2024; Agora: Klimaneutrales Deutschland, 2045, 2019; BMDV: Verkehr in Zahlen, 2023; Prognos, 2021a)

4.4. Processed data

The preprocessing and analysis of statistical data from KBA and the responsible German Federal Ministry is needed to develop a robust fleet model. These data are processed to generate key preprocessed datasets essential for modeling fleet evolution; this is true for survival rates, age distributions, and distance-driven patterns by propulsion technology (petrol, diesel, CNG, LPG, HEV, PHEV, BEV, and FCEV).

Analysis was conducted on vehicle age profiles for each propulsion technology, revealing insights into how fleet composition evolves as vehicles age (see (Github, 2025)). Survival rates, essential for determining the probability of vehicles remaining operational over their lifespan, were empirically derived by combining recent micro-datasets (available from 2014 onward) with long-term historical data from official registration reports of the German Federal Motor Transport Authority (KBA) reports dating back to 1950. This methodology provided a robust baseline survival curve reflecting historical German consumer behavior without major behavioral shifts such as modal changes or widespread car-sharing adoption. A sharp drop in survival rates observed between two and three years of vehicle age corresponds to typical lease expirations and subsequent exports or transitions into the private vehicle market (Fig. 2 (left); supplementary 5). Due to limited data availability, especially concerning recent propulsion technologies like BEVs and FCEVs, the survival rates for BEVs were conservatively assumed to mirror those of petrol cars. While longer BEV lifetimes are technically plausible, vehicle structure, design lifetimes, and consumer replacement behavior might remain limiting factors. Different survival assumptions would shift the absolute fleet composition but not the relative scenario trends. This assumption aligns with recent battery longevity findings (Hackmann et al., 2024) and similar methodological approaches (Fridstrøm, 2022a, 2022b).

Annual vehicle distance driven per propulsion technology was derived using transport-power data grouped by age categories from (BMDV, 2022). A curve-fitting methodology minimized the discrepancies between observed grouped data and the developed annualized distance-driven model (Fig. 2 (right); supplementary 4). For BEVs specifically, annual distance driven was estimated by blending the distance-driven profiles of diesel (one-third) and petrol (two-thirds) vehicles, reflecting the gradual replacement of conventional technologies. While this ensures comparability across scenarios, it does not account for possible future changes in usage behavior as charging infrastructure improves. However, recent shifts in consumer behavior – such as transitions from diesel to petrol or PHEV vehicles due to diesel restrictions in urban areas – may not be fully captured by this historical data-based approach, signaling a limitation of the method.

Due to the short historical coverage, the used database is insufficient to establish reliable, representative survival rates for certain technologies like BEVs and FCEVs being relatively new technologies undergoing rapid advancements in longevity. The assumption of petrol-based survival rates for BEVs may underestimate actual battery durability, potentially leading to longer-than-projected lifespans. Data inconsistencies exist, especially in historical records prior to 2014, necessitating interpolation and extrapolation techniques that could introduce additional uncertainty. Survival rates and distance-driven patterns were treated as static, time-invariant parameters that did not account for potential future changes in consumer behavior, modal shifts, or technological improvements. Also, annual distance-driven estimates for BEVs do not yet reflect actual usage patterns distinct from conventional vehicles due to limited historical data availability.

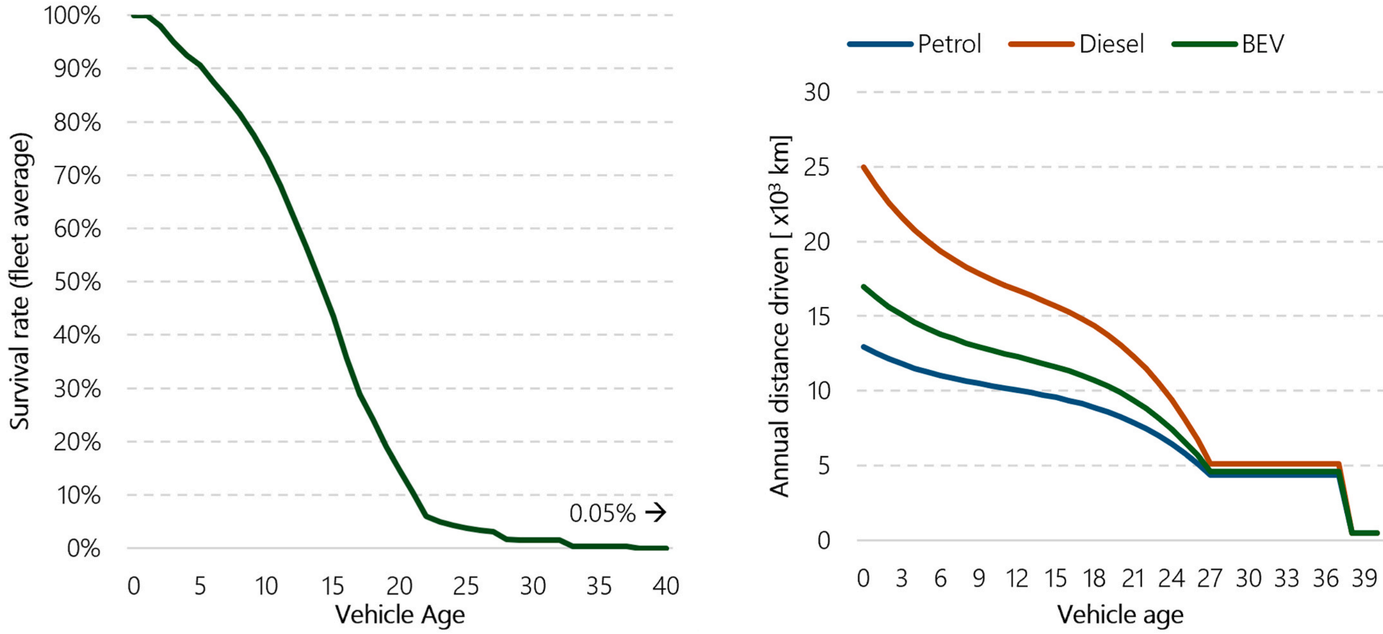

Fig. 2. The empirically developed average survival rate of cars in Germany (left) [this study] and annual distance driven by vehicle age and technology (right) (Kraftfahrt-Bundesamt, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h).

4.5. Scenario definition

This study designed several scenarios to explore the potential pathways for the adoption of BEV in the vehicle fleet. These scenarios provide insights into the impacts of different rates of BEV penetration, as well as their implications for final energy demand and CO_2 tailpipe emissions. In each scenario, the market shares of all other technologies are adjusted accordingly to meet the targeted BEV and PHEV shares defined exogenously. Table 4 shows the scenarios designed.

S100 is defined as a base scenario and will be used compared to other studies (section Table 4.) Fig. 3 (left) illustrates the new registrations per technology in S100 being elaborated below (for other scenarios see supplementary Spreadsheet Model Dashboard). In Fig. 3, the period labeled “Data” (2014–2022) is based on official registration statistics from the German Federal Motor Transport Authority. From 2023 onwards, the “Scenario” segment begins, where new registration shares are defined exogenously according to the scenario assumptions summarized in Table 4. From 2035, the EU regulation requiring zero tailpipe CO_2 emissions is applied, leading to the phase-out of conventional ICE registrations. Only the S80 and S100+ scenarios deviate from the regulation-compliant trajectory, with S80 allowing a residual PHEV share of 20 % by 2035 and S100+ reaching full BEV adoption only in 2040.

Table 4
Scenario characteristics.

Scenario	BEV new registrations share (by 2035)	BEV Adoption Pattern	ICE Ban Fulfillment	PHEV-Share by 2035	Comments
S100	100 %	S-curve until 2035	Fulfilled	0 %	Moderate s-curve ramp-up
L100	100 %	Flat until 2035, then jump to 100 %	Fulfilled	0 %	Negative marginal scenario
S100+	100 % by 2040	S-curve until 2040	Belated	0 %	Belated s-curve ramp-up
Linear100	100 %	Linear increase until 2035	Fulfilled	0 %	Linear increase
S80	80 % BEV, 20 % PHEV	S-curve	Not fulfilled	20 % (PHEV: 2/3 petrol, 1/3 diesel)	Mixed adoption scenario

The share of BEV new registrations (green line) steadily increases over time, reaching 100 % by 2050. This reflects a transition towards full electrification of new vehicle registrations, consistent with the scenarios aiming for complete BEV adoption and current CO_2 performance standards. Both diesel (orange line) and petrol (blue line) powered new registrations decrease significantly over this period. The decline in diesel is sharper than petrol, suggesting a faster reduction in diesel-powered vehicles, likely due to regulatory pressure (e.g., environmental zones) and shifting consumer preferences. PHEV shares (purple for petrol PHEV, dark blue for diesel PHEV) show a slight initial increase but turnover before 2030 and declines to zero by 2035 as BEV adoption accelerates. This indicates that PHEVs could have a transitional role before full electrification. Petrol and diesel HEVs (light blue and light green, respectively) also see a gradual decline, indicating a similar transitional role as PHEVs. Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG), and Fuel Cell Electric Vehicles (FCEV) show minimal shares throughout the period. Their adoption remains limited compared to BEVs.

Fig. 3 (right) illustrates the different pathways only for BEV adoption across all scenarios from 2014 to 2050. Despite the differences in adoption speed, all scenarios converge at a 100 % BEV share for new registrations by 2035 due to the indirect ICE ban, besides the S80 scenario. S80 aims for 80 % BEV adoption by 2035, with a remaining PHEV share of 20 % until 2050. The scenarios display distinct ramp-up patterns: S100+ is similar to S100 but reaches 100 % BEV adoption in new registration later in 2040 instead of 2035, representing a potential shift of the CO_2 performance standards goal due to a potential EU moratorium (CDU, 2022) and incorporates a dip of EV sales after the end of the environmental bonus (German Government, 2023). L100 demonstrates a delayed adoption, with BEV shares remaining constant based on 2023 values until 2035, followed by a sudden increase to 100 %, highlighting the opposite marginal scenario. S100, S80, and Linear100 exhibit more

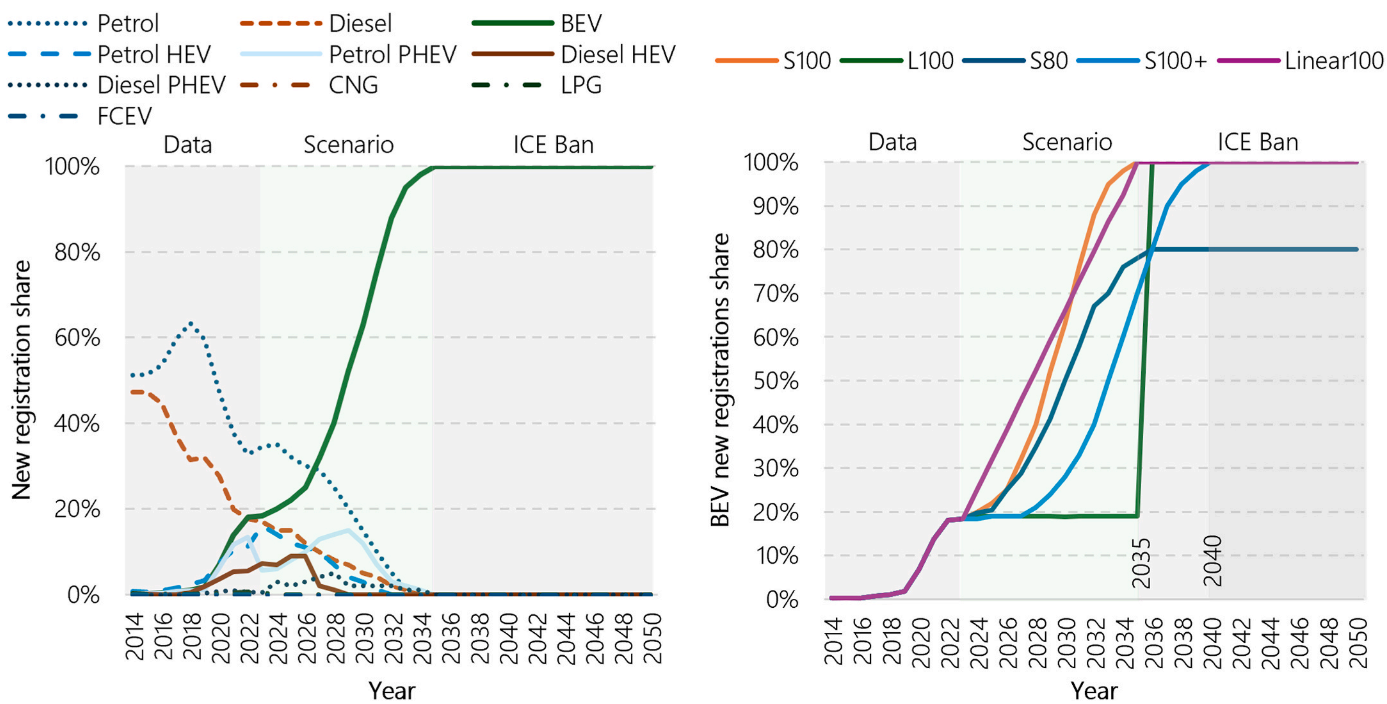

Fig. 3. New registrations in the S100 scenario by powertrain (left) and shares of BEV new registrations across all scenarios (right). The period 2014–2022 ("Data") is based on official registration statistics from the German Federal Motor Transport Authority (KBA) (Kraftfahrt-Bundesamt, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f, 2022g, 2022h). From 2023 onwards ("Scenario"), new registration shares are defined exogenously according to the assumptions in Table 4. From 2035 ("ICE Ban"), the EU regulation requiring zero tailpipe CO_2 emissions for new passenger cars is applied. Among the scenarios, only S80 (80 % BEV, 20 % PHEV) and S100+ (delayed full BEV adoption by 2040) deviate from this regulation-compliant trajectory.

gradual adoption patterns, with S100 and S80 reflecting an S-curve pattern typical of the Bass diffusion model, while Linear100 shows a steady linear increase. The extreme scenario (L100) is particularly relevant for illustrating the differences in cumulative CO_2 emissions and represents a 'no-market-adoption' scenario until the regulation forces a shift to 100 % BEV registrations.

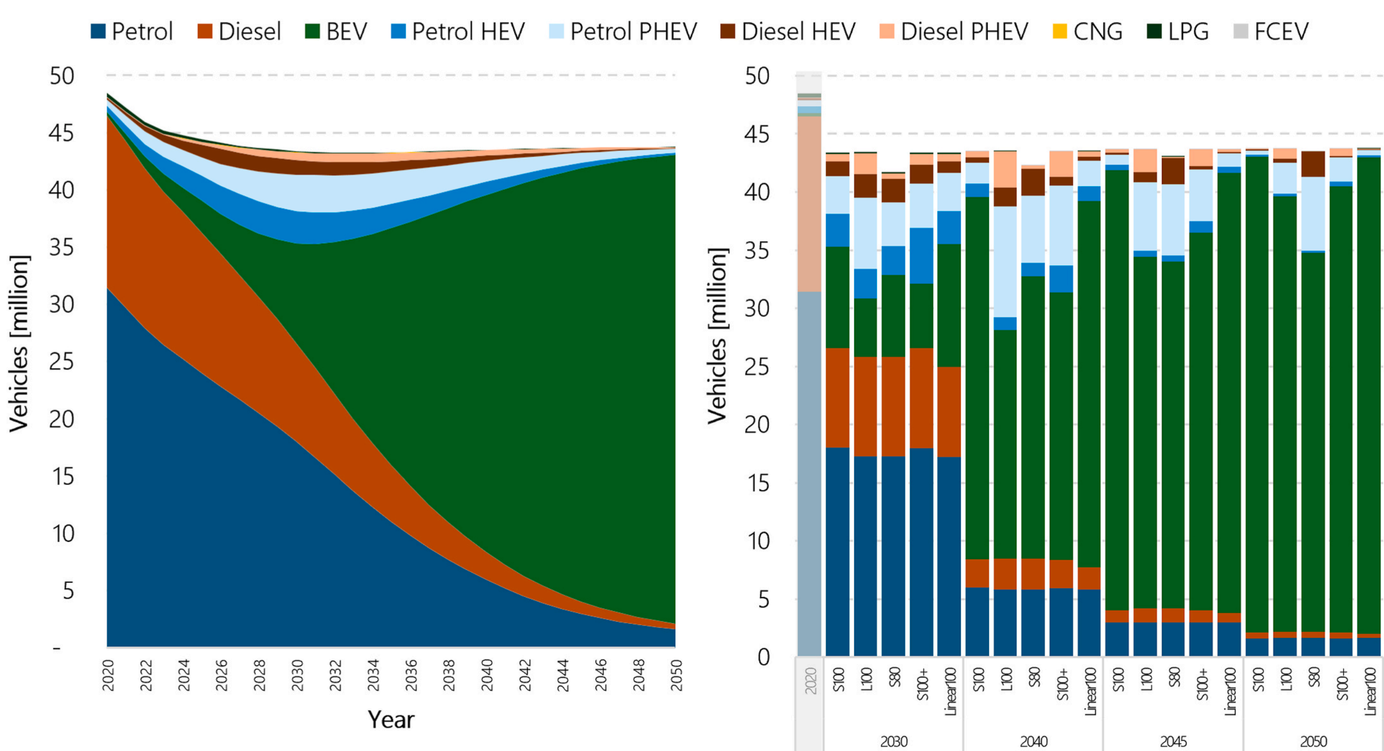

Fig. 4. Evolution of vehicle fleet composition from 2020 to 2050 under scenario S100, illustrating the transition from internal combustion engine vehicles (petrol and diesel) to BEVs and other technologies [left]; comparison of fleet compositions across scenarios at selected years (2025, 2030, 2040, 2045, 2050) [right]. Statistical data are displayed for comparison in 2020. After 2020, projections are illustrated.

The scenarios defined above highlight the varying impacts of policy and market dynamics on BEV adoption, emphasizing both rapid and moderate transitions (for further information and new registration curves of other technologies see supplementary Spreadsheet Model).

5. Results and discussion

The following sections present, illustrate, and interpret the results of the fleet development, final energy demand, and tailpipe CO_2 emissions analyses. Each subsection first describes outcomes under the baseline scenario “S100” before comparing all defined scenarios. Historical data from 2014 to 2022 were validated against official German statistics (BMDV: Verkehr in Zahlen, 2023) to ensure model accuracy (Supplementary Fig. 12–16, supplementary section 6). The fleet developments are most critical, as final energy demand and CO_2 emissions are directly derived from vehicle stock.

5.1. Fleet development

The transformation of the German vehicle fleet follows a clear shift from ICE vehicles to BEVs, with projections highlighting distinct transition speeds across different consumer adoption pathways. Fig. 4 illustrates this shift, with the left panel detailing the fleet evolution within scenario S100 and the right panel providing a comparative overview of fleet compositions across various electrification scenarios at selected milestone years (2030, 2040, 2045, 2050). Initially, actual data from 2020 highlight petrol and diesel dominance, reflecting historical market conditions.

In 2020, ICE vehicles dominated the fleet, with petrol and diesel cars comprising the vast majority. Electrification remained marginal, with BEVs representing only a fraction of total registrations. By 2025, projections indicate an increasing presence of BEVs, though traditional powertrains still dominate, particularly in scenarios with weaker BEV adoption.

The shift to electrification gains momentum after 2030, as BEVs become the dominant technology in new vehicle registrations, and transitional hybrid powertrains – both plug-in hybrids (PHEVs) and hybrid electric vehicles (HEVs) – peak before gradually declining. Differences between adoption patterns in the transitions become increasingly apparent. Overall, diesel and petrol cars show similar counts across all scenarios in 2030 but differ in composition of BEV and PHEV. In S80 and L100 PHEVs serve a significant transitional role towards later BEV uptake. By 2040, most scenarios converge toward electrification, as ICEs decrease further as none are newly registered anymore due to the CO_2 performance standards since 2035 besides minor new registrations in S100+.

BEVs remain the major choice as assumed in the scenarios. By 2050, near-total electrification is reached across all scenarios, with BEV shares ranging from 86 to 97 %. The remaining ICE vehicle presence is minimal, largely confined to slow turnover effects and collector vehicles, resulting from the remaining oldtimer share seen in the data. While alternative powertrains such as fuel cell electric vehicles (FCEVs) and gas-powered options (CNG, LPG) exist in some scenarios, their impact remains marginal related to the overall picture. The trajectory across scenarios underscores the policy's decisive role – especially CO_2 performance standards in shaping the transition's speed and effectiveness.

The transition follows an S-curve pattern, with a sharp BEV uptake after 2030, driven by the CO_2 performance standards regulation. PHEVs and HEVs act as transitional solutions, peaking around the 2030s before phasing out as BEV adoption becomes dominant. But it could be also possible that the ratio of PHEV/HEV changes depending on the exact design of the respective CO_2 performance standards. Legacy ICE vehicles persist longer in L100 due to slower turnover, highlighting the limitations of policy-driven phase-outs. Alternative powertrains remain negligible, as CNG, LPG, and FCEVs fail to gain market traction under strong electrification pathways. Gradual transitions in S100, S80, S100+ and Linear100 ultimately lead to high BEV penetration, even if early targets are missed. Despite different ramp-up behaviors, all scenarios converge toward near-total BEV adoption by 2050, reinforcing the long-term effectiveness of strong regulatory measures.

The projected transition in the German vehicle fleet from predominantly fossil fuel-based vehicles in 2020 toward near-complete electrification by mid-century is heavily influenced by the defined adoption curves for new vehicle registrations between the mid-2020s and the mid-2030s. From 2025 onwards, projections reveal increasing divergence across ramp-up scenarios, underscoring the sensitivity of fleet evolution to assumptions regarding technology uptake rates.

The static survival rates and the constant driving behaviors assumed here might overestimate the speed of vehicle turnover; also, recent data show an increasing average age of cars in Germany. Furthermore, the assumption that ca. 0.3 % of the vehicles are transferred into the "Oldtimer phase" characterized by minimal annual distances driven (around 500 km/a) results in a residual ICE presence even within strongly electrified scenarios. This assumption highlights a realistic market segment that sustains minimal fossil fuel demand beyond primary electrification phases, contributing slightly to tailpipe CO_2 emissions even in 2050. Interestingly, the shift of the CO_2 performance standards deadline from 2035 to 2040 results in just slightly lower BEV shares in 2045 and 2050 but does significantly enlarge the use of ICEs. However, it shows a slightly higher remaining fleet of HEVs, as they might be a viable option to achieve the reduced goals for a longer period in this scenario. The ICE shares are similar in both scenarios, while the PHEV option loses relevance in comparison.

Fig. 5 compares the study's projections (scenario S100) for the German vehicle fleet with prominent system studies at selected milestone years (2030, 2045, and 2050), highlighting differences in fleet compositions and underlying assumptions. In 2030, the projected fleet size (44 M vehicles) aligns closely with other system studies, though it remains slightly lower than other estimates (e.g., SKN-Agora and Ariadne-REMod Mix (Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021; Prognos, 2021b),). While all studies anticipate significant electrification by 2030, this model shows a somewhat higher persistence of plug-in hybrid electric vehicles (PHEVs) reflecting uncertainties around consumer adoption rates and the transitional role of hybrid technologies during early electrification phases. By 2045, the scenarios developed here forecast ca. 44 M vehicles, closely matching other projections (e.g., Ariadne-DLR Mix and SKN-Agora (Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021; Prognos, 2021b),), yet slightly below other studies (e.g., Ariadne-REMod Mix and TIMES-PanEU Mix; around 50–52 M vehicles) (Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021; Prognos, 2021b). At this stage, BEVs dominate across all analyses. Still, this study again differs in terms of a higher residual ICE presence, reflecting slower vehicle turnover rates or differing assumptions about policy impacts and vehicle lifespans. In the year 2050, the convergence toward electrification across all scenarios is clearly visible. This projection of 43 M vehicles is comparable to the BMWK LF5 TN Strom scenario (40 M vehicles (Gnann et al., 2024a),), but slightly higher than other studies, underscoring different assumptions regarding market dynamics or vehicle retirement patterns. Although the BEV penetration assumed here aligns with most studies, a slightly longer-lasting ICE presence is anticipated here, not least due to the remaining Oldtimer fleet. This difference likely stems from factors such as collector vehicles, the influence of vintage cars, or more conservative scrappage assumptions, highlighting critical uncertainties regarding consumer behavior and regulatory effectiveness (BCG, 2021; Dena: dena, 2021; Gnann et al., 2024a; Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021; Prognos, 2021b; Stiftung Klimaneutralität, 2022).

5.2. Final energy demand and tailpipe CO_2 emissions

Below the results related to the final energy demand as well as the

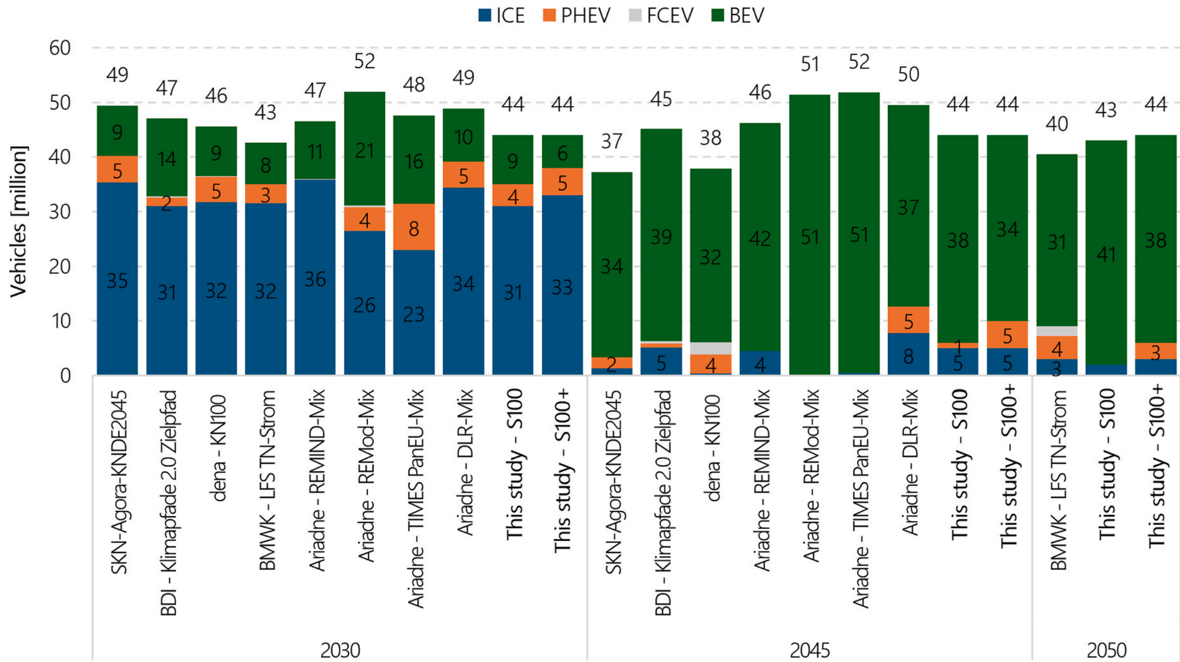

Fig. 5. Comparison of our results to the five major energy system studies in Germany (BCG, 2021; Dena: dena, 2021; Gnann et al., 2024a; Ariadne and Kopernikus-Projekt, 2021; Klimaneutralität et al., 2021; Prognos, 2021b; Stiftung Klimaneutralität, 2022).

CO_2 tailpipe emissions are discussed in detail.

Final Energy Demand. Fig. 6 presents the evolution of final energy demand (FED) by powertrain technology under scenario S100 (left panel) and provides a comparative overview across different ramp-up scenarios for technology adoption at selected milestone years (right panel).

In scenario S100, actual data from 2020 show that the final energy demand remained heavily dominated by petrol and diesel vehicles, representing basically the overall energy demand at that time. From the mid-2020s onwards, projections indicate a notable shift toward electrification, primarily driven by increasing registrations of BEVs. By mid-century, the final energy demand from petrol and diesel declined dramatically to minimal levels, reflecting a near-complete replacement by BEVs accounting for ca. 91 % of the total final energy demand by

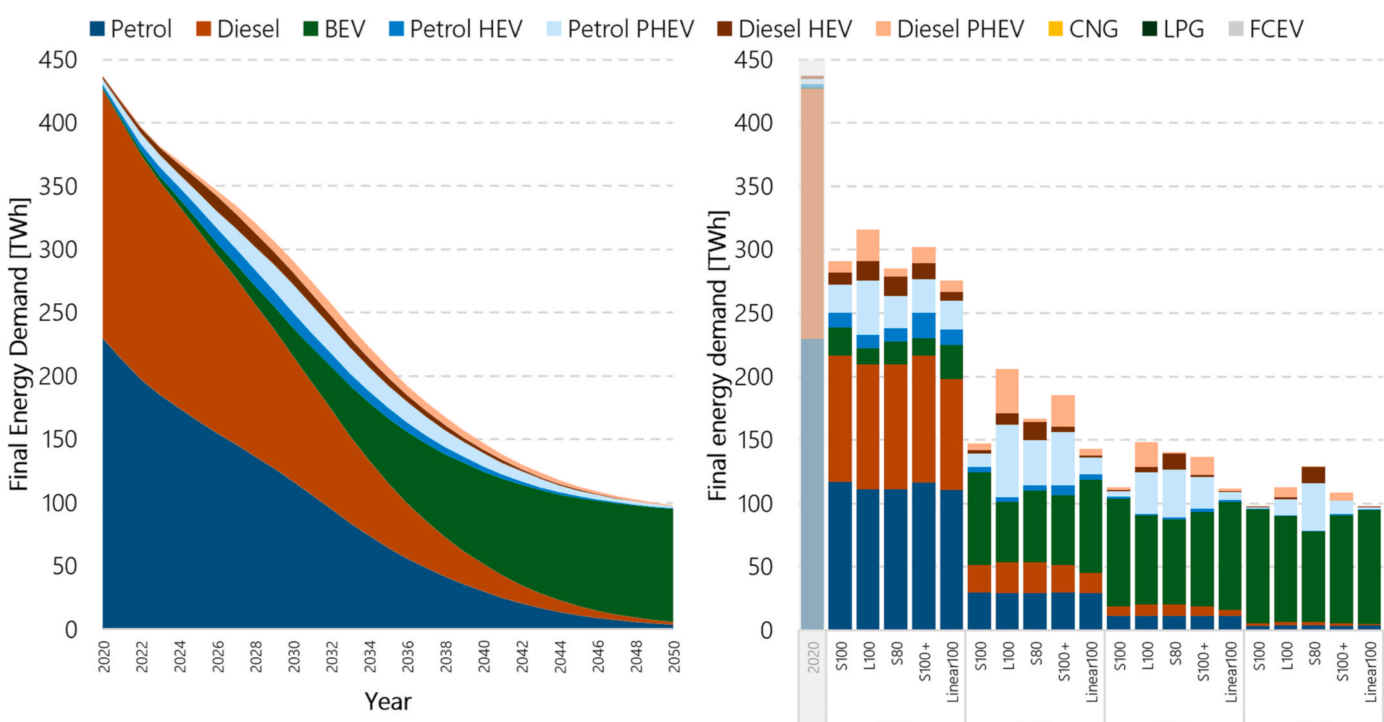

Fig. 6. Final energy demand by powertrain technology under the S100 scenario (2020–2050) [left]; Final energy demand trends for each propulsion technology over time, highlighting the transition from petrol and diesel to electric energy as the dominant source for the vehicle fleet [right]. Statistical data are displayed for comparison in 2020. After 2020, projections are illustrated.

2050. Plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) temporarily fill transitional roles, with energy demand peaking in the early 2030s before declining as BEVs take precedence. Alternative technologies such as compressed natural gas (CNG), liquefied petroleum gas (LPG), and fuel cell electric vehicles (FCEVs) remain marginal throughout.

Comparing ramp-up scenarios across selected years (right panel), differences in the speed of technological shifts become obvious. In 2020, real data confirm petrol and diesel dominance; the final energy demand from BEV is negligible. By the projected year 2030, substantial variations emerge. L100 contrasted sharply to other scenarios, as it projects a slower technology shift and maintains higher petrol and diesel demand. By 2040, most scenarios (S100, S100+ Linear100) indicate that BEVs dominate the final energy demand, while scenario L100 continues to show significant fossil fuel dependency. By the year 2050, near-complete electrification is projected across all scenarios, though minor fossil fuel use remains in the slower ramp-up scenario (L100). Faster ramp-ups significantly accelerate the reduction in fossil fuel demand, emphasizing the importance of timely technology adoption to achieve energy transition targets efficiently. Also, the total transport power is not constant over time within the various scenarios, potentially underestimating the FED required to meet the distance-driven (see Supplementary Fig. 8). This effect is related to the assumed distance-driven profile of BEVs, which underestimates the distance-driven for diesel, especially between the vehicle age 0 to 4 (see Supplementary Figs. 12 and 18). The results indicate that the electrification of the car fleet shows in a significantly lower FED, decreasing by more than 75 % between 2020 and 2050.

Tailpipe CO_2 Emissions. Fig. 7 shows the evolution of tailpipe CO_2 emissions by propulsion technology for scenario S100 (left panel) and compares emission trends across different technology ramp-up scenarios at selected milestone years (right panel).

- In the year 2020, actual data reveal that tailpipe CO_2 emissions were overwhelmingly dominated by petrol and diesel vehicles, totaling to ca. 116 Mt.
- From the mid-2020s onwards, projections indicate substantially declining CO_2 emissions, driven by improved fuel efficiency and the growing adoption of hybrid and (BEVs.
- By the year 2030, total CO_2 emissions across scenarios fall notably, reflecting reduced petrol and diesel consumption due to increased electrification. The transitional role of plug-in hybrid electric vehicles (PHEVs) becomes evident, temporarily contributing to the CO_2 emissions but serving as an intermediate step toward BEV adoption. However, differences in technology ramp-up scenarios significantly affect the emissions trajectory.
- By 2040, transitional technologies such as PHEVs and HEVs remain present in the vehicle stock in scenarios including L100, S80, and S100+, although their shares differ substantially: small residual cohorts in L100, a continued 20 % share in S80, and a gradual phase-out in S100+
- By mid-century, tailpipe CO_2 emissions are nearly eliminated across all scenarios, underscoring the complete transition from fossil fuel-powered vehicles to electric mobility. The near-zero emissions in 2050 reflect both the shift in final energy demand towards electricity and the assumption of a zero-emission factor for electricity in the transport sector under sectoral emission accounting. In this framework, emissions from electricity generation are counted within the power sector rather than the transport sector. Scenarios with faster technological transitions achieve more rapid declines in emissions, underscoring the central role of electrification in meeting climate targets, whereas slower transitions prolong fossil fuel dependence and illustrate the risks of delayed fleet transformation.

The substantial reduction in tailpipe CO_2 emissions closely aligns with the final energy demand (FED) shift from fossil fuels to electricity. Initially, emissions are primarily driven by petrol and diesel consumption, as indicated by statistical data from the year 2020. However,

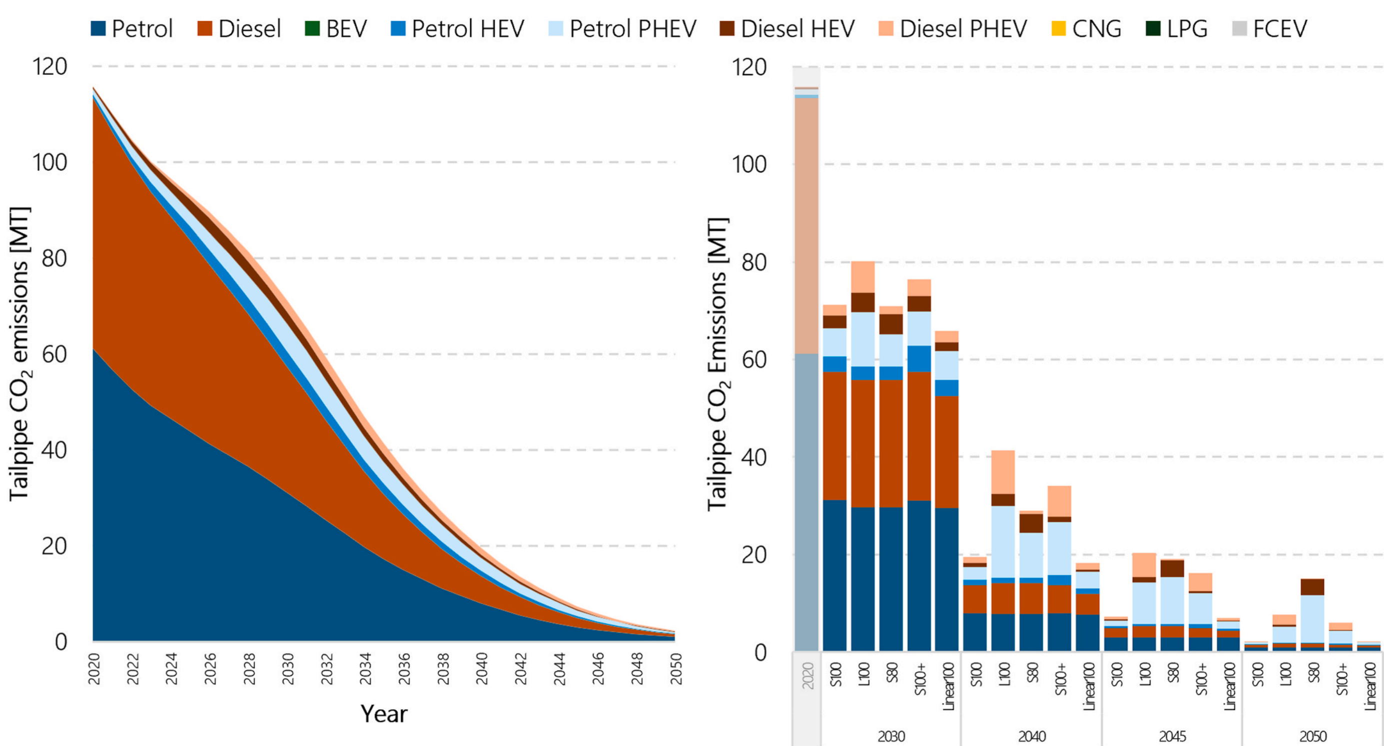

Fig. 7. Tailpipe CO_2 emissions by year and technology under scenario S100 [left]; Comparison of scenarios for tailpipe CO_2 emissions [right]. Statistical data are displayed for comparison in 2020. After 2020, projections are illustrated.

starting from the year 2025, projected emissions decline corresponding closely to increased adoption of BEVs and improvements in vehicle efficiency.

Furthermore, since the model assumes a 10 % electric distance-driven share for PHEVs globally and remains static over time, it might underestimate the emissions-reduction potential of PHEVs in future years.

Discussion. Fig. 8 compares the final energy demand (FED) projections from this study (S100) with selected other scenarios (T45-Strom, T45-H2, T45-PTG/PTL, O45-Strom, O45-H2) (Gnann et al., 2024a). In the base year (2020), historic data show petrol (150 TWh/540 PJ) and diesel (226 TWh/778 PJ) overwhelmingly dominating the final energy demand, with marginal contributions from gas and BEVs, reflecting minimal electrification at that time. By 2030, the projected final energy demand significantly declines across all scenarios (ranging from 253 to 291 TWh/911 to 1048 PJ). The S100 scenario projection (291 TWh/1048 PJ) is slightly higher than the others, primarily due to greater contributions from petrol and diesel vehicles. The general alignment of BEV energy demands (51–63 TWh/184 to 227 PJ) across all scenarios highlights broad agreement on electric vehicle adoption trajectories, whereas differences in the overall final energy demand likely arise from divergent assumptions regarding annual distances driven, consumer driving behavior, and specific vehicle consumption patterns. In 2045, this projection (113 TWh/407 PJ) closely aligns with most other scenarios, notably T45-Strom and O45-Strom (102–103 TWh/367 to 371 PJ) (Gnann et al., 2024a, 2024b). However, the higher final energy demand observed in scenario T45-PTG/PTL (138 TWh/497 PJ) (Gnann et al., 2024a, 2024b) stems from sustained petrol and diesel demand, potentially reflecting higher assumptions on annual vehicle distance driven or slower changes in consumption behavior as some studies explicitly assume a shift to other transport modals. Conversely, scenarios emphasizing hydrogen (e.g., T45-H2 and O45-H2) show higher hydrogen demand (16–32 TWh/57 to 115 PJ) (Gnann et al., 2024a, 2024b), illustrating alternative energy diversification pathways and potential deployment of FCEV within the mobility sector. Given the lack of explicitly communicated underlying assumptions, differences in the final energy demand most likely result further from varying assumptions regarding fuel consumption behavior and the speed of fleet turnover. Such parameters influence energy demand projections but they are often implicit or unreported. Overall, comparative analysis highlights both convergence and divergence in projections, particularly driven by differences in implicit behavioral assumptions rather than explicitly communicated technological or policy scenarios.

In interpreting these results, it's crucial to recognize the conservative assumption that PHEVs operate only about 10 % of their distance within the electric mode (empirical usage pattern of company cars assumed (Plötz et al., 2022)) – at the lower end compared to data from (Plötz et al., 2022), which found that charging behavior of company and private PHEVs ranges from 10 to 40 %. As cars become more digitally connected, the available data should be more reliable and granular in the years to come. Moreover, a higher electric-driving share in PHEVs would reduce total FED due to higher efficiency of the electric powertrain, as it slightly increases electricity demand but reduces petrol/diesel fuel in a higher manner. This aspect is particularly relevant for the tailpipe emissions and remains a sensitive assumption during the transitional phase until 2035.

Future market and policy developments could significantly change the usage patterns of PHEVs and BEVs. With rising shares of variable renewable electricity, vehicle charging is expected to become a shiftable load within demand-side management. This flexibility could support grid stability and reduce charging costs for consumers, as electricity prices tend to be lower during periods of high renewable generation. In addition, increasing demand for balancing power and energy services could further strengthen the business case for electric vehicles. Advances in battery technology – particularly improvements in energy density and larger battery capacities – will allow newer PHEV models to offer considerably higher electric ranges. Additionally, legal requirements stipulate that PHEVs must achieve a minimum electric range (e.g., at least 80 km from 2025 onwards) (Volkswagen: 0) in order to qualify for tax credits or incentives. These rules could motivate consumers to increase their share of electric driving. Such policy-driven and technological shifts would substantially increase PHEVs' actual electric share, potentially leading to greater CO_2 emission reductions than the scenario assumptions outlined above suggest. This underscores the sensitivity of the final energy demand projections to underlying assumptions and emphasizes the need for transparency in reporting such factors to better interpret results in future comparative analyses.

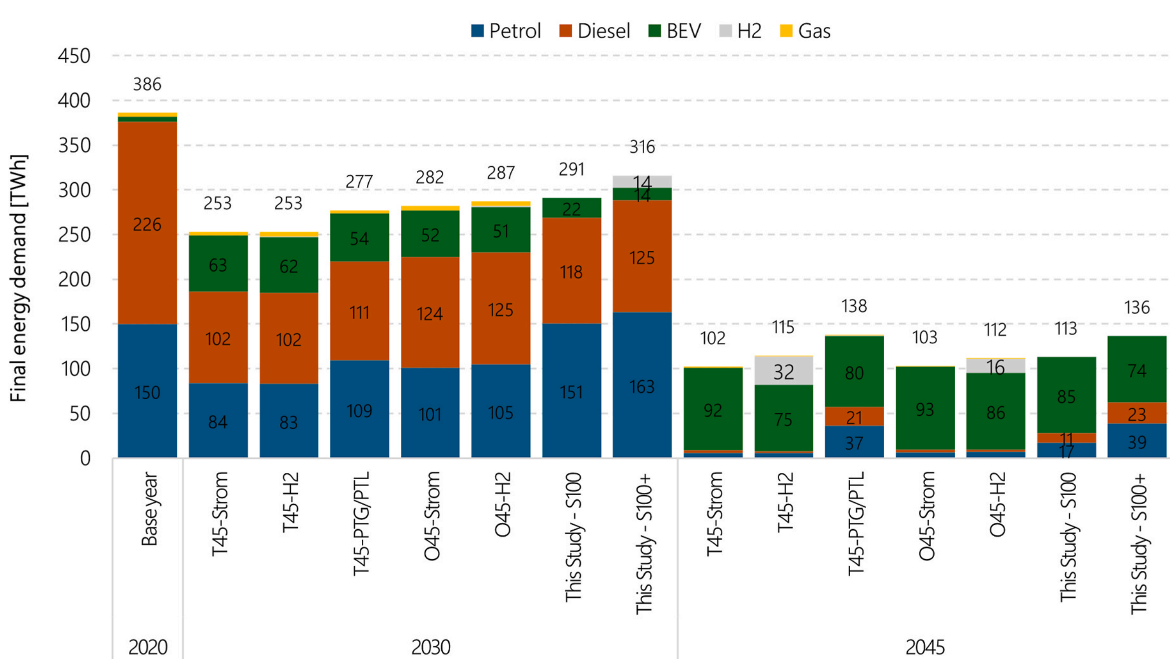

Fig. 8. Comparison of final energy demand results with selected studies (Gnann et al., 2024a, 2024b). Statistical data are displayed for comparison in 2020. After 2020, projections are illustrated.

5.3. Accumulated tailpipe CO_2 emissions

The overall influence on climate of different ramp-up scenarios can be better understood by analyzing the accumulated CO_2 emissions. Therefore, Fig. 9 illustrates the accumulated tailpipe CO_2 emissions from 2020 to 2050 across the defined scenarios. Further, all scenarios are analyzed by adding CO_2 emission from electricity production. Although current carbon accounting does not consider those within the transport sector, such a procedure provides valuable insights into the overall CO_2 emissions. The striped areas represent additional CO_2 emissions resulting from electricity consumption in corresponding sub-scenarios (S100CO$_2$, L100CO$_2$, etc.), where the CO_2 emission factor for electricity declines linearly from 0.4 kg CO_2/kWh in 2020 to zero by 2050 (see Supplementary Fig. 7).

Scenario S100 serves as a baseline, accumulating 1.5 Gt tailpipe CO_2 emissions over the period 2020 to 2050. Including the emissions from the used electricity (scenario S100CO$_2$) the cumulative emissions increase by ca. 13 %. Across all scenarios, the cumulative total CO_2 emissions (including electricity provision) raises between 7 % (L100/L100CO$_2$) and 17 % (Linear100/Linear100CO$_2$), illustrating how the timing of electric vehicle (BEV) adoption impacts overall CO_2 emissions.

Scenario S100+, characterized by the shift of the deadline to 2040, exhibits a relatively moderate increase (+8 %) when electricity emissions are considered. This is primarily because it introduces a large BEV fleet later compared to S100 when electricity generation is already less carbon-intensive. Conversely, scenario L100, featuring delayed BEV adoption (with 100 % BEV registrations from 2035 onward), benefits from lower electricity-related CO_2 emission factors at the time of significant BEV integration, resulting in a relatively small CO_2 emission increase (+7 %). However, the overall accumulated CO_2 emission in L100 remain substantially higher compared to S100 and even scenario S80 achieving intermediate electrification speeds but maintains a residual presence of plug-in hybrid electric vehicles (PHEVs).

Overall, a shift of the CO_2 performance standards deadline from 2035 to 2040 results in an increase of +16 % (S100+/S100) under current CO_2 accounting scheme (scope 1). If CO_2 will be accounted for in the end-use sector, the emissions still increase by +11 % (scope 2). Therefore, a shift of the deadline to reduce transformational pressure on the automotive industry comes at a cost 195 to 241 Mt accumulated CO_2 emissions for the German car sector.

6. Final considerations

6.1. Summary and conclusion

Germany's road-transport transition is already under way, but its end-point and the cumulative climate impact depend critically on how fast battery-electric vehicles (BEVs) displace cars with an internal-combustion engine (ICE) within the overall car fleet in the years to come. Against this background this study analyzes Germany's vehicle fleet evolution from the mid-2020s to 2050, highlighting pathways to achieve climate neutrality. Therefore, several scenarios are explored representing different speeds of electrification and adoption rates of alternative propulsion technologies. Each scenario is analyzed related to fleet composition, final energy demand, tailpipe CO_2 emissions, and accumulated CO_2 emissions under varying technological and policy assumptions. The following overarching insights emerge.

- **Speed matters far more than the final state.** All scenarios investigated here reach more than 86 % BEV share in the car stock fleet by 2050, yet their cumulative tailpipe CO_2 emissions between 2020 and 2050 differ by almost 0.5 Gt CO_2. A five-year delay in the 100 %-BEV registration goal (scenario S100 vs. scenario S100+) raises cumulative transport-sector CO_2 emissions by ~16 % under the present scope 1 accounting and by ~11 % once electricity-sector emissions are attributed to end-use (scope 2). Early electrification therefore outweighs the temporary penalty of charging from a partially fossil power mix.
- **Legacy ICEs are the long tail of the problem.** Even in the most ambitious case, some 3–4 M ICE cars remain on the road in 2050, largely because of slow scrappage of today's vehicles – indicated by an increasing average vehicle age – and a small, quasi-immortal oldtimer segment. These residual cars consume <10 % of final transport energy but account for most remaining tailpipe CO_2 emissions in 2050. Measures that accelerate fleet turnover – e.g., targeted scrappage schemes, restricted city access for high-emitting vehicles or incentives for ICE retrofits – could close this "last-mile" emissions gap without altering consumer choice for new cars.
- **Policy coherence across sectors is decisive.** Tight fleet CO_2 standards have proved indispensable in steering manufacturer supply and consumer uptake, yet their credibility is being challenged by calls for a regulatory moratorium. Weakening or postponing the 2035 target would lock in 195–241 Mt additional CO_2 emissions and jeopardize Germany's 2045 neutrality goal. At the same time, the

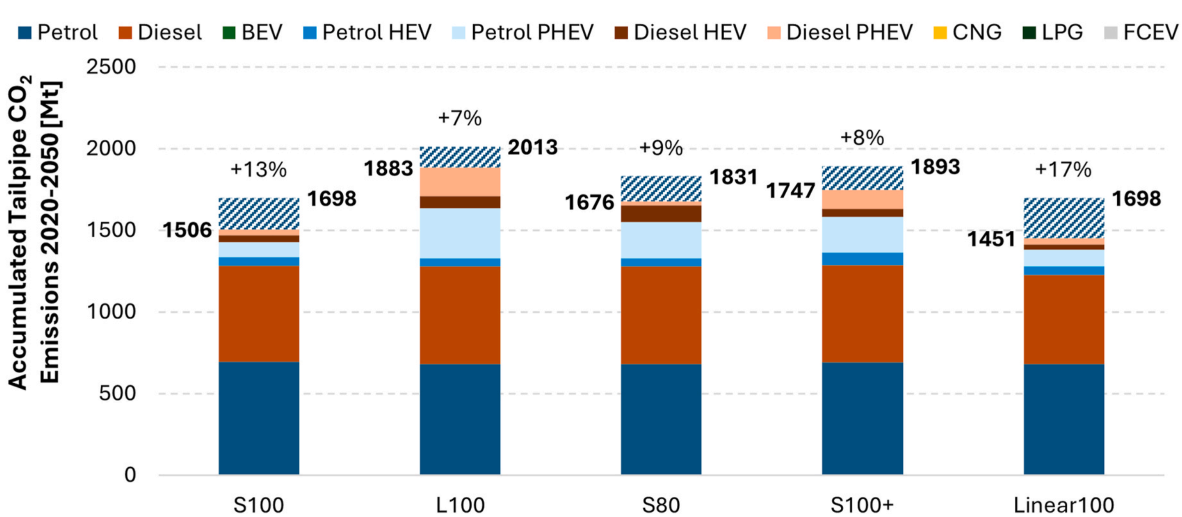

Fig. 9. Accumulated tailpipe CO_2 emissions (2020–2050) for the different scenarios. If considered, the striped area represents the CO_2 emissions from electricity provision for each scenario. The percentage right above the area quantifies the gain due to consideration.

planned EU-ETS2 will finally expose road fuels to a rising carbon price, aligning consumer costs with climate externalities.

Substantively, the results show that Germany can still meet its transport-sector carbon budget, but only if (i) 100 % zero-emission sales are locked in no later than 2035, (ii) commercial fleets – 70 % of new registrations – are prioritized for rapid BEV turnover, and (iii) complementary instruments tackle charging behavior, PHEV electric-drive shares, and the residual ICE niche. Integrating these insights into forthcoming revisions of EU fleet standards, national climate legislation and the ETS2 design will be decisive for translating the projected 98 % tailpipe CO_2 reduction in 2050 into a proportionate cut in cumulative CO_2 emissions – and for safeguarding Germany's pathway to net-zero mobility.

It should be noted that the analysis covers operational emissions (tailpipe and electricity-related) only. CO_2 emissions from battery production, which can be substantial in lifecycle assessments, were not included. A comprehensive sensitivity analysis of survival rates, usage patterns, and PHEV electric-driving shares was beyond the scope of this study. These assumptions affect absolute energy demand and CO_2 projections, but the overall conclusions regarding the decisive role of early BEV adoption remain robust. Future extensions of the FLEETCAST model will address these sensitivities in more detail. Further, these emissions depend heavily on the electricity mix used in manufacturing and are expected to decline over time as production decarbonizes and recycling improves. In the present model, BEV driving patterns are based on a weighted blend of historical petrol and diesel usage (two-thirds petrol, one-third diesel), serving as a neutral empirical proxy in the absence of representative long-term BEV data. This simplification does not imply continuing range anxiety or infrastructural constraints but provides a transparent, technology-neutral baseline for comparability across scenarios. Assuming static usage patterns until 2050 is therefore a conservative simplification. Future BEV usage may increase as charging infrastructure expands and ranges improve, leading to higher electricity demand, or decrease under modal shifts and shared mobility. These effects would influence the magnitude of energy demand but not the relative scenario trends or the central conclusion on the decisive role of CO_2 performance standards. Assuming a fixed 10 % electric-driving share for PHEVs is a conservative simplification. Higher shares, which are plausible with improved charging infrastructure and ownership patterns, would reduce emissions further and strengthen the robustness of the main findings. The deterministic model structure does not capture economic feedbacks (e.g., ICEV price dynamics, infrastructure interactions) or quantify uncertainty ranges. Instead, uncertainty is represented through contrasting scenario pathways. Future work will extend the framework with stochastic or feedback-based approaches to assess uncertainty more comprehensively. Long-term projections to 2050 inevitably involve significant uncertainty. Static assumptions regarding usage behavior, technology progress, and policy continuity simplify reality but allow transparent scenario comparisons. While this limits the precision of absolute values, the relative scenario differences - particularly regarding the timing of BEV adoption - remain robust.

6.2. Outlook

Based on the results outlined above the following additional aspects arise.

Electricity generation from renewable sources of energy. The results highlight the critical importance of accelerating the transition to BEVs. Despite initially higher electricity-related emissions, early BEV adoption offers significant long-term climate benefits due to higher energy efficiency and the displacement of fossil fuel use within the transport sector.

The assumed linear decline in electricity CO_2 emission factors reflects Germany's 2045 climate neutrality goal by simplifying complex and uncertain future developments. In reality, CO_2 emissions from electricity production will depend heavily on the increased use of renewable sources of energies – especially wind and solar – and on the overall electricity demand, which is expected to rise sharply due to increasing electrification within industry and the heating sector. Without corresponding progress within the defossilization of the electricity sector, the climate benefits of BEV adoption may fall short of their full potential.

Therefore, achieving real-world climate benefits requires continued parallel defossilization of the electricity sector itself. Without a sustained growth of an electricity generation from renewable sources, the sectoral assumption risks overstating the actual CO_2 emissions benefits from electrification, as higher electricity demand of the transport sector without a corresponding expansion of renewable capacity in parallel might result potentially in higher usage of electricity generation by thermal power plants using fossil fuel energy. Additionally, adequate measures need to be implemented to enable charging of the BEV fleet that is aligned with electricity generation patterns, particularly the availability of renewable energy.

CO_2 performance standards in light of EU ETS2 expansion. CO_2 performance standards have historically played – and still play in 2025 – a key role in reducing CO_2 emissions from internal combustion engine (ICE) vehicles by incentivizing efficiency improvements, engine downsizing, and the early adoption of hybrid and electric technologies. The CO_2 performance standards are aimed at vehicle manufacturers (OEMs) and not at end consumers, creating a discrepancy between regulatory pressure and consumers' purchasing decisions regarding vehicle and drive technology. With the introduction of the EU ETS2, carbon pricing is extended to the transport sector, potentially resolving this gap, creating a push-pull mechanism. Unlike CO_2 standards, EU ETS2 is a market-based instrument that puts a direct price on CO_2 emissions at the point of fuel purchase. It increases the cost of operating ICE vehicles and makes BEV use relatively more attractive. However, this price signal alone may not be sufficient to trigger a fast and broad consumer transition. Several factors might limit BEV uptake:

- High upfront costs, especially for households that already own a functioning ICE vehicle.
- Practical limitations, particularly for those without private charging options – e.g., residents of apartment buildings without access to workplace charging or public infrastructure.

If these barriers persist, OEMs may struggle to meet fleet-wide CO_2 targets, potentially resulting in penalties despite their limited ability to influence consumer behavior directly. This creates a risk of financial strain for manufacturers, particularly in countries like Germany with a strong automotive industry and significant employment tied to OEMs. Meanwhile, rapid cost declines in battery cells – driven by chemistries such as lithium iron phosphate and emerging sodium-ion, as well as blended-chemistry packs – are steadily eroding the upfront-price gap.

In response, political pressure could lead to calls for the softening, delay, or even suspension of CO_2 performance standards (CDU, 2022). But weakening standards before carbon pricing is fully internalized would likely slow down, not smooth, the transition.

Policy implications. In light of these dynamics, integrated cross-sectoral policy planning is essential. The defossilization of the transport sector must go hand in hand with the defossilization of the electricity sector and the evolution of the respective regulatory frameworks. Several measures are worth considering:

- Accelerated expansion of EU ETS2. A quicker rollout of the second emissions trading system (ETS2), ideally with integration into the existing ETS1, could create stronger and more coherent incentives across sectors.
- Transition from scope 1 to scope 2 accounting within ETS. Currently, emissions from electricity generation are attributed to the energy sector under scope 1, while fossil fuel use in cars is accounted for in

the transport sector. Economically, it does not make a difference, as costs are handed over to the end user anyway, but it is resulting in an unrepresentative emission balance. A shift toward scope 2 accounting – i.e., tracking CO_2 emissions at the point of electricity use – would make transport sector CO_2 emissions more transparent in the context of electrification. For ICEs, this would have minimal effect, but for BEVs, it would clarify the climate impact of charging behavior.
- Introduction of dynamic electricity tariffs. Fixed electricity tariffs dilute the impact of consumer behavior. In contrast, time- and carbon-sensitive pricing signals on the end-user could incentivize charging during periods of high renewable availability and grid availability, if network charges become dynamic too. This would enhance the integration of BEVs into the energy system, enable demand-side management, and support grid stability. Combined with vehicle-to-grid (V2G) capabilities, BEVs could even provide localized storage and balancing services. Temporal and spatial data collection is key to track charging behavior, derive representative CO_2 emission balances, and create specific (incentive) policies for renewable energy usage and grid stabilization during charging of road vehicles.

Overall, these considerations point to the need for adaptive and forward-looking policy frameworks. Only through the coordinated transformation of the transport and energy systems, transparent CO_2 emissions accounting, and well-aligned incentives for both producers and consumers can Germany and the EU achieve their long-term climate and industrial goals. Further, future policies should therefore address both rapid BEV deployment and measures encouraging higher electric usage in PHEVs, exploiting their full CO_2 emissions mitigation potential to ensure ambitious decarbonization targets are achieved.

CRediT authorship contribution statement

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

Submission declaration

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

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

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

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Abbreviations

Abbreviation	Meaning
BEV	Battery Electric Vehicle
BMWK	German Federal Ministry for Economic Affairs and Climate Action
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ETS	European Emission Trading Scheme
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FED	Final Energy Demand
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
KBA	German Federal Motor Transport Authority
LPG	Liquefied Petroleum Gas
Mt	Million tons
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PTG/PTL	Power-to-Gas/Power-to-Liquid
TWh	Terawatt-hour

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tranpol.2026.103994.

Data availability

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

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