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Quantifying the impact of fleet turnover on electric vehicle uptake in Europe

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ABSTRACT

To achieve the EU's decarbonization targets of the passenger car fleet by 2050, additional measures are required that go beyond the current policy. This paper presents a modular approach to project the future composition of the EU's passenger car fleet, focusing on battery electric vehicles (BEVs). The methodology combines a bottom-up transportation model to estimate new BEV registrations with a country-specific empirical model based on survival rates to estimate the future BEV fleet composition. Findings show a significant increase in vehicle lifespan across the EU since 2008, posing a barrier to rapid fleet electrification. Assuming constant 2021 survival rates until 2050, the European BEV stock share is projected to reach 85% by 2050. Restoring turnover rates to 2008 levels could increase this share to 92%, while continued increases in vehicle life could lower it to 78%. Significantly different levels of passenger car fleet electrification across EU Member States are observed.

1. Introduction

1.1. Motivation

Decarbonizing passenger car transport can significantly reduce CO_2 emissions and mitigate climate change. This can be achieved through several strategies: reducing the use of passenger cars (e.g., by teleworking), shifting transportation modes (e.g., from road to rail or from sport utility vehicles (SUVs) to light electric vehicles (LEVs) (Ehrenberger et al., 2022)), and transitioning from high-pollution technologies (e.g., vehicles that emit carbon dioxide by burning fossil fuels) to less polluting options like Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs). Plug-in Hybrid Electric Vehicles (PHEVs), while sometimes considered a transitional technology, are not the focus here due to their higher real-world emissions (Mandev et al., 2024). This paper introduces a model to estimate the BEV stock shares across the EU and performs a sensitivity analysis to examine various factors influencing BEV adoption in the EU's passenger car fleet. By analyzing these factors, the study aims to identify pathways to accelerate the transition to a decarbonized transportation sector. The focus on BEVs is due to their continuous advancements in performance and affordability, which position them as the most viable and promising technology for achieving significant reductions in CO_2 emissions (Domarchi and Cherchi, 2023; Plötz, 2022; Hasselwander et al., 2023).

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Various studies have explored the key factors driving BEV adoption across different regions, such as financial incentives (Hardman et al., 2017), emission targets (Senzeybek et al., 2024), infrastructure deployment, and improvements in battery technology (Hasselwander et al., 2025) and battery range (Hasselwander, 2025). Additionally, these studies examine the characteristics of early electric vehicle (EV) adopters, identifying demographic and behavioral patterns that influence purchase decisions (Jia and Chen, 2021, 2023; Hardman et al., 2016). However, for BEV mass adoption, it is crucial to address not only these initial factors but also less-studied aspects like the discontinuance behavior among EV owners, which can pose challenges to sustained growth (Hardman and Tal, 2021). To support BEV adoption, a range of policies has been implemented across the EU, including CO_2 emission reduction targets that set future emission levels and provide incentives for manufacturers to invest in and innovate within the EV sector (Axsen et al., 2022).

The EU has defined a clear roadmap to reduce CO_2 emissions through a series of directives aimed at achieving net-zero emissions from newly registered vehicles by 2035 (European Commision, 2022). However, the rate of transition to zero-emission vehicles (ZEVs) until 2035 will vary among EU countries due to differences in policy implementation, market dynamics, and consumer behavior, thereby affecting the fleet composition and overall decarbonization progress by 2035 (Möring-Martínez et al., 2024). While increasing the share of ZEVs is critical for reducing emissions, the extent of decarbonization will largely depend on the turnover rates of the existing vehicle stock (Figenbaum et al., 2015; Chatzikomis et al., 2014). Current data shows significant variation in the average lifespan of passenger cars across the EU, ranging from 8 to 35 years as of 2016 (Held et al., 2021), highlighting the different rates of electric vehicle adoption that can be expected across different member states.

The European Green Deal sets a goal of reducing greenhouse gas emissions from transport by 90% by 2050, aiming for the EU to become climate-neutral (Comission, 2021). However, to align with the Paris Agreement's goal of limiting global warming to 1.5 °C, net-zero emissions may need to be achieved earlier, by 2044-2048 (Plötz et al., 2023). To accelerate the shift to a zero-emission vehicle fleet and help meet these targets, this paper focuses on analyzing how the composition of the European vehicle fleet, particularly the increase in BEVs, will develop up to 2050. This paper focuses on modeling the composition of the European vehicle fleet, particularly the increase in BEVs, to evaluate how different substitution dynamics rates could support the EU's climate targets up to 2050. Understanding vehicle turnover dynamics and increasing BEV adoption will be essential for reaching these goals.

1.2. Existing literature

Different models can be used to forecast new vehicle registrations and the stock fleet composition. Bottom-up models, such as discrete choice models (DCM), evaluated by Domarchi and Cherchi (2023), seem to provide more accurate results than top-down approaches, which often simplify or overlook individual behavior. Examples of DCMs include those by Brand et al. (2017), Jensen et al. (2017) and Oliveira et al. (2019). The benefits of bottom-up models are the possibility of modeling with a reduced amount of aggregated data (Peres et al., 2010). Hybrid or mixed models combine bottom-up and top-down approaches (Jochem et al., 2018). These models can offer a more realistic representation of the system and its interactions, but require increased data acquisition and processing efforts (Domarchi and Cherchi, 2023).

Given the complexity and significant data requirements of these models, to our knowledge, almost no models are available for modeling the EU stock fleet at the member-state level or for other large groups of countries. One notable example is the mixed model presented by Pasaoglu et al. (2016), which covers the EU and uses uniform survival rates assumed from Germany, derived from the PRIMES-TREMOVE model (Ntziachristos et al., 2008; E3Mlab, 2014; Gómez Vilchez et al., 2019). This approach overlooks country-specific variations in vehicle survival rates, a significant limitation given the diverse turnover rates of vehicle fleets across different EU countries.

Cohort models such as those by Oguchi and Fuse (2015) and Held et al. (2021) use survival rates to predict fleet turnover and composition changes. Survival rates indicate the proportion of vehicles from a specific age group that remain registered within a country, relative to the total number of vehicles newly registered in their initial year. These models rely on cumulative survival probability (CSP) curves, which indicate the likelihood of a car remaining in the fleet at a certain age. The CSP curve reflects the characteristics of a country's vehicle fleet and its car owners, capturing socioeconomic factors unique to each nation (Vanherle and Vergeer, 2016). In Europe, used cars often move west-to-east, with higher-income countries replacing older vehicles that are then used longer in lower-income regions, resulting in higher average vehicle ages in Eastern Europe (ACEA, 2022b).

Oguchi and Fuse (2015) provide survival rates for 17 countries as of 2008, while Held et al. (2021) offer data for the entire EU (excluding Bulgaria) and additional countries for 2016. However, survival rates can change significantly over time, as observed by Oguchi and Fuse (2015) and Held et al. (2021). Therefore, it is important to analyze these changes and update the curves accordingly to keep the model updated. Held et al. (2021) improves upon previous cohort models by addressing their limitations, especially for countries where the used car market is predominant, such as in Eastern Europe. This methodology enables the update of CSPs for all EU countries using existing data sources, making it applicable to models forecasting new vehicle registrations across the EU.

In the field of bottom-up models, Redelbach et al. (2013) offers a model that maximizes a linear utility function to estimate new vehicle registrations. By using a clustering approach, Möring-Martínez et al. (2024) extends these results to estimate future new passenger car registrations for entire EU member states with reduced data requirements. The combination of Möring-Martínez et al. (2024) and Held et al. (2021) allows the estimation of BEV stock shares across the EU.

1.3. Contribution of this study

Despite the advances in modeling approaches, several research gaps remain. First, there is a lack of updated CSP curves that reflect current conditions for all EU countries, limiting the accuracy of existing models. Second, many models do not account for country-specific survival rates, leading to potential inaccuracies when applied across diverse regions. Third, there is a need for a modular approach that integrates different modeling techniques to provide a comprehensive and adaptable framework for analyzing stock fleet composition across the EU. Finally, increasing transparency in modeling practices can enhance the accuracy, reproducibility, and continuous improvement of existing approaches.

This study addresses these research gaps and contributes to the literature by implementing a modular approach that combines a bottom-up model (Möring-Martínez et al., 2024) with a multi-country cohort model based on empirical survival rates (Held et al., 2021). The research aims to:

1. **Update Country-Specific CSP Curves:** The study updates CSP curves for all EU member states to the year 2021, providing a more accurate and current empirical model. This update allows for comparisons of CSP curves over time – from 2008 (Oguchi and Fuse, 2015), 2016 (Held et al., 2021), and 2021 – to assess their impact on stock shares.
2. **Define an EU vehicle stock model:** The study presents a straightforward and transparent implementation of CSP curves within a bottom-up model for modeling future EU member passenger car stock alternative powertrain (particularly BEV) shares, alongside a validation using historical data.
3. **Analyze substitution dynamic effects:** A sensitivity analysis illustrates the effect of substitution dynamics, emphasizing the importance of turnover rates and new vehicle registration share rates in accelerating the electrification and decarbonization of the EU vehicle stock.
4. **Open-Source model:** The model is fully transparent and open-source, enabling users to run, validate, and further develop it. All data and code are publicly available in Möring-Martínez (2025) to promote collaboration and continuous refinement.

2. Methodology and data

2.1. Bottom up-model: Modeling of new vehicle registrations by powertrain

The projection of new vehicle registrations by powertrain in EU Member States is based on the bottom-up approach developed by Möring-Martínez et al. (2024). The bottom-up model follows a two-stage framework (cf. Eq. (1)): first, countries are clustered based on similarities in their transition towards net zero-emission vehicle registrations; second, the evolution of new vehicle registrations is simulated in a representative country within each cluster using an agent-based utility maximization vehicle choice model. The resulting shares of new vehicle registrations by powertrain for the different clusters, $R_{t,C,p}$, are used to approximate adoption patterns across all countries and the EU. The two-step structure of the model is formally represented in Eq. (1), where clustering (C) groups countries with similar characteristics, and utility maximization determines the share of new vehicle registration R by powertrain p in each year t for each cluster C ($R_{t,C,p}$).

$$\begin{aligned} &\text{Step 1: Clustering} \rightarrow C \\ &\text{Step 2: Utility maximization on clusters } (C) \rightarrow R_{t,C,p} \end{aligned} \tag{1}$$

This approach addresses data limitations at the country level and reduces the need for exhaustive input data by grouping EU Member States into seven clusters according to the maturity of their passenger car markets in adopting alternative powertrains. Clustering is based on 11 key variables – such as charging infrastructure availability, BEV market share, and national taxation schemes and subsidies – selected through an extensive literature review and authors' expertise. To mitigate multicollinearity, Principal Component Analysis (PCA) is applied prior to hierarchical clustering, which is subsequently consolidated with k-means to generate stable and interpretable country groupings. Countries within each cluster are assumed to share similar structural characteristics and market trajectories.

For each cluster, a representative country is simulated using VECTOR21, a hybrid market penetration model combining agent-based modeling with discrete choice theory under a utility maximization framework (cf. Fig. 1). The model integrates both demand-side factors-such as household income, annual mileage, place of residence, taxation, and infrastructure availability-and supply-side factors, including vehicle cost, powertrain characteristics, and technology learning curves. Agents are segmented into different adopter categories that reflect different degrees of openness to innovation and sensitivity to environmental attributes. These categories influence how agents evaluate vehicle options, particularly in terms of willingness to pay for low-emission technologies. Moreover, technical characteristics like driving range and acceleration are assessed with different levels of importance depending on the agent group, representing the diversity in consumer priorities. This approach allows the model to simulate realistic choice behavior across heterogeneous user profiles, capturing the dynamic evolution of powertrain adoption over time under varying policy and market conditions.

Policy and macroeconomic inputs are exogenous variables modeled under a Stated Policies Scenario (STEPS) and include EU-wide CO_2 targets, national tax regimes, and energy price forecasts. Finally, the model output obtained is a yearly forecast until 2035 of new vehicle registrations disaggregated by powertrain type (e.g., BEV, G-PHEV, ICE) for each cluster. The resulting projections are then extrapolated to all countries within the corresponding clusters, allowing for a robust, data-efficient projection of the EU-wide transition to alternative powertrains.

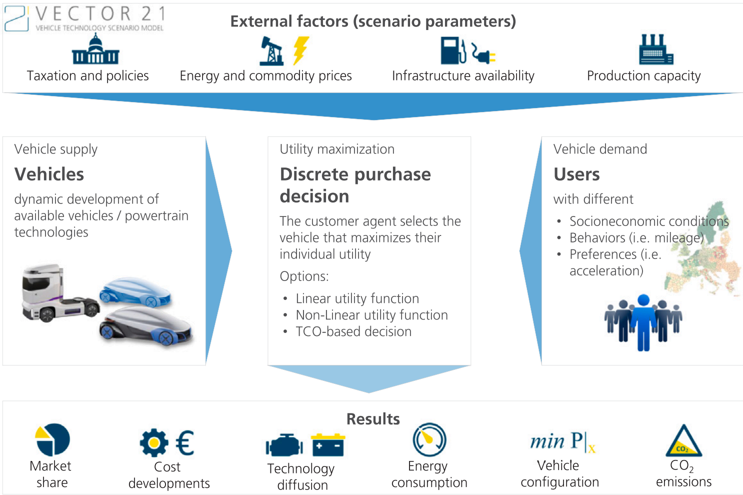

Fig. 1. Method of bottom-up vehicle technology scenario model VECTOR21.
Source: Figure extracted from Institute of Vehicle Concepts (DLR) (2023).

In the simulated scenario, BEVs are projected to dominate future zero-emission vehicle registrations across Europe. However, the model shows that countries follow different electrification pathways, with BEV shares increasing progressively at varying rates across clusters through 2035. For example, by 2030, BEV sales are projected to reach about 30% in Eastern countries, 50% in Southern countries, 70% in Central European countries, and nearly 100% in Scandinavian countries. The modeling by Möring-Martínez et al. (2024) is extended to 2050 in this study. Throughout the period, the share of FCEVs remains negligible, staying below 2% all years in all countries.

While the bottom-up agent-based model captures many techno-economic and behavioral factors influencing powertrain adoption, it does not explicitly model social diffusion processes such as peer effects, word-of-mouth, or evolving social norms. Alternative approaches include dynamic discrete choice models that adjust parameters over time to reflect social influence (Zhang et al., 2011; Sweda and Klabjan, 2011; Struben and Sterman, 2008), and frameworks integrating psychological traits and individual attitudes to better capture adoption motivators (Tchetchik et al., 2020; Liao et al., 2017). Incorporating such social and psychological dynamics is complex and remains a promising direction for future research to enhance the realism and accuracy of vehicle technology adoption forecasts (Domarchi and Cherchi, 2023). While other models may incorporate these dynamics differently, Möring-Martínez et al. (2024) offers a comprehensive and data-efficient framework that balances behavioral realism and computational tractability, making it a suitable choice for long-term powertrain adoption forecasting despite these limitations.

2.2. Cohort model: country-specific survival probability estimation

To determine fleet turnover, the age-specific number of surviving vehicles is estimated using the cohort model developed by Held et al. (2021). This model estimates the cumulative survival probability (CSP) of vehicles, reflecting the likelihood that a car of a given age remains in a national fleet. CSP is a core element in fleet turnover models used to forecast vehicle stock evolution, especially in the context of electrification and emissions reduction. Importantly, CSP characterizes national fleets and owner behaviors – not individual vehicles – and is strongly influenced by economic conditions, scrappage patterns, and cross-border trade in used cars. The method empirically calculates CSP curves from annual vehicle registrations and vehicle stock by age (Oguchi and Fuse, 2015), formalized as:

$$CSP_t(a) = \frac{N_t(a)}{R_{t-a}} \tag{2}$$

where $N_t(a)$ is the number of cars of age a in the stock at time t, and R_{t-a} is the number of new car registrations at the time of their entry into the fleet $t-a$.

The model captures age-dependent survival dynamics by fitting empirical CSP data with parametric functions (cf. Fig. 2). Traditionally, a Weibull distribution represents the age-related scrappage of vehicles (dark blue curve in Fig. 2). However, in countries with significant used car imports, the CSP curve deviates from this shape due to the addition of older imported vehicles. To address this, the model enhances the standard Weibull curve by adding a Gaussian component, which models the influx of imported vehicles at preferred ages. The resulting Weibull–Gaussian composite function accounts for both natural aging and import effects (orange curve in Fig. 2). Held et al. (2021) show that this formulation significantly improves the fit to empirical data across 31 European countries, increasing the average goodness of fit R^2 from 0.73 (Weibull-only) to 0.90 (Weibull–Gaussian). The combined

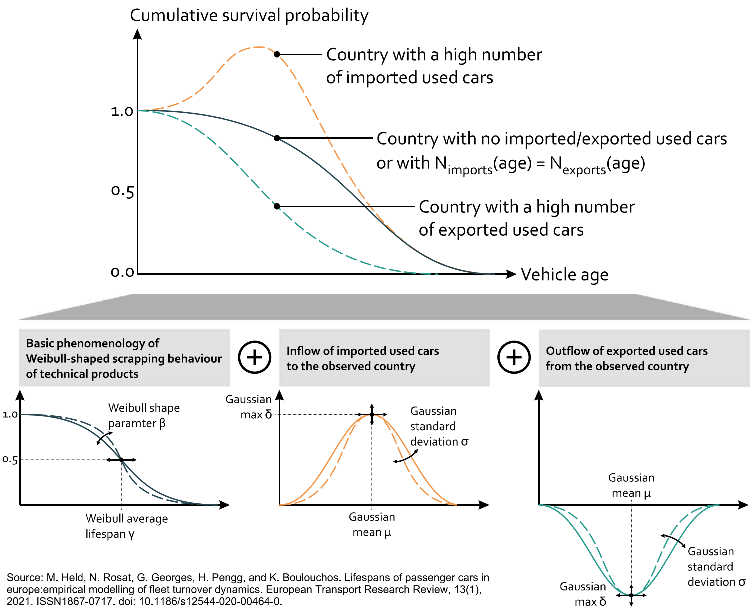

Fig. 2. Characteristic cumulative survival probability (CSP) curves from Held et al. (2021). Countries with no imports/exports (dark blue), high imports (orange), and high exports (turquoise) of used cars. Empirical CSP values from Eq. (2) are shown in the upper panel; their phenomenological approximation is illustrated in the lower panel. Fitting parameters β, γ, δ, μ, and σ refer to the Weibull and Gauss distributions (Eqs. (3) and (4)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: Figure extracted from Held et al. (2021).

approach (Held et al., 2021) is summarized as:

$$CSP(a) \leftarrow W(\beta, \gamma, a)\ for\ countries\ without\ considerable\ imports \tag{3}$$

$$CSP(a) \leftarrow W(\beta, \gamma, a) + N(\delta, \mu, \sigma, a)\ for\ countries\ with\ considerable\ imports \tag{4}$$

where W indicates a Weibull function and N a Gaussian function. $\beta, \gamma, \delta, \mu, \sigma$ are statistical parameters (specifically, β is the shape parameter, γ is the average lifespan, μ is the mean and σ is the standard deviation) and a is the age of the vehicle.

Inputs of the model include vehicle stock by age and new registrations from European national statistics offices. While the method does not explicitly require data on used vehicle imports and exports, it implicitly accounts for import dynamics via the Gaussian component fitted to empirical CSP deviations. The model is applied to EU countries plus Norway, each yielding a country-specific set of parameters. The output is a continuous CSP curve predicting the share of vehicles remaining in use at any given age.

These CSP curves are vital for fleet turnover and emissions modeling, improving accuracy across countries with different vehicle markets and lifespans. For example, empirical data from 2016 (Held et al., 2021) show that average vehicle lifespans in European countries vary significantly, ranging from approximately 8.0 to 35.1 years. A pronounced West-East divide is observed, with used vehicle flows from Western to Eastern Europe resulting in substantially older fleets in the East. Given the high volume of used car imports in several target countries of this study, the Weibull–Gaussian approach offers a more accurate estimation of fleet turnover than traditional cohort models.

2.3. Stock model

The stock model integrates the bottom-up model with clustering from Möring-Martínez et al. (2024) and the CSP curves approach from Held et al. (2021) (cf. Fig. 3). It simulates the passenger car stock by year t, vehicle age a, and powertrain type p, using the projected new registrations (cf. Eq. (1)) and empirical vehicle survival curves (cf. Eqs. (3) and (4)).

$$N_{t,c,p}(a) = CSP_{t,c}(a) \cdot R_{t-a,c,p} \tag{5}$$

Here, $N_{t,c,p}(a)$ represents the number of vehicles in stock at time t in country c, of powertrain type p, and age a. The term $R_{t-a,c,p}$ denotes the number of new registrations at the time of their entry into the fleet $t-a$, for country c and powertrain p, while $CSP_{t,c}(a)$ is the cumulative survival probability of a vehicle of age a in country c at time t. This formulation assumes that a fraction of vehicles registered in year $t-a$ survives to year t according to the empirical CSP curves.

This flexible approach allows modifications to either the CSP curves or the scenarios for new vehicle registrations by powertrain.

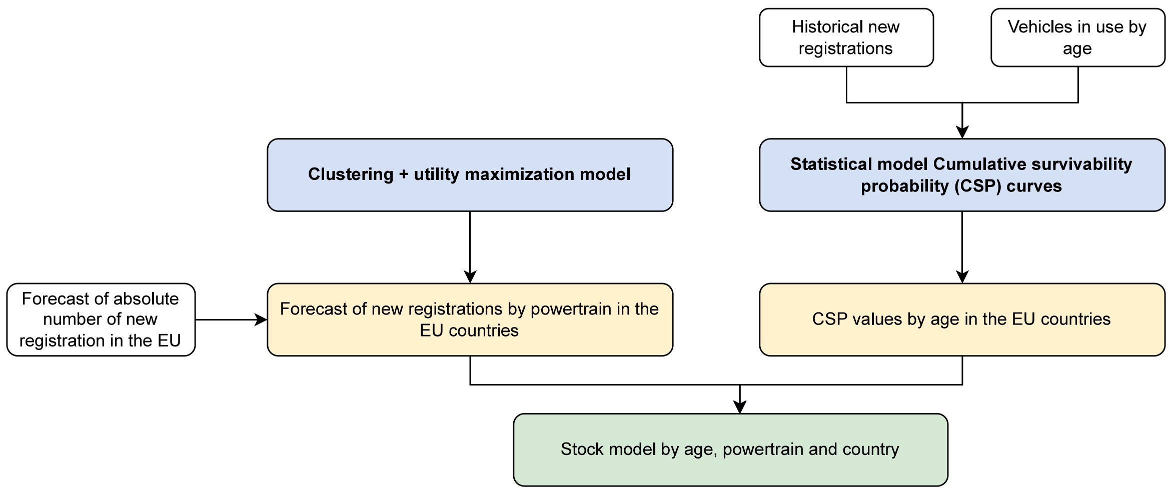

Fig. 3. Methodology for modeling stock fleet share in EU member states. The methodology combines the bottom-up model with clustering developed by Möring-Martínez et al. (2024) and the CSP curve approach introduced by Held et al. (2021). This model's flexibility allows for the definition of various scenarios, providing insights into how these scenarios might impact the stock.

3. Results and discussion

3.1. Cohort model: country-specific survival probability estimation

To analyze the cohort model's performance, we update the cumulative survival probability (CSP) values to the year 2021. We have collected data on vehicle stock and new registrations for 32 European countries. Using Eq. (2), we calculate the empirical CSP data for 2021. Subsequently, we apply the methodology from Held et al. (2021) to fit this CSP data using both Weibull (cf. Eq. (3)) and Weibull-Gaussian curves (cf. Eq. (4)) for all countries. Further information on data sources, fitting parameters, optimal distributions, and the goodness of fit of the curves is provided in Appendix A.

As discussed, the survival rates of a country's passenger car fleet vary over time (Oguchi and Fuse, 2015; Held et al., 2021). CSP fitting parameters thus have to be updated regularly to correctly capture the dynamics of the fleet. In the model, one key parameter is the Weibull average lifespan (γ), which describes the characteristic time at which vehicles are typically retired from the fleet. This parameter is closely related to the average age of the vehicle stock and shows a strong empirical correlation across countries studied ($R^2 = 0.87$). This relationship supports the use of γ as a robust proxy for tracking changes in fleet turnover over time, particularly in the absence of detailed longitudinal data on scrappage or used car imports (cf. Appendix A.4).

The temporal evolution of the average lifespan for 11 European countries is analyzed at three different years (cf. Fig. 4): 2008 (Oguchi and Fuse, 2015), 2016 (Held et al., 2021), and 2021 (own calculation). For the remaining EU countries, data is available only for two years: 2016 and 2021.

In Fig. 4, we can observe that between 2008 and 2021 the average lifespan either stays almost constant or increases in all 11 European countries. For the rest of the countries with available data since 2016, we see a decrease only in Poland and an increase in the rest of the countries shown. Between 2008 and 2016, the EU-9 weighted average lifespan[1] increased by 13% and between 2016 and 2021, by 11%. Between 2016 and 2021, the EU-26 weighted average lifespan increased by 8%. Additionally, between 2016 and 2021, data disaggregated by age show that the average age of the EU-26 fleet increased by 7%. There is an increasing trend in the lifespan of the vehicles in the last 14 years in the EU.

A longer lifespan for the vehicle fleet has significant implications for efforts to decarbonize the fleet because an aging stock could slow down the transition to electric vehicles. Without the implementation of scrappage schemes, the rate of fleet electrification may lag behind expectations due to the current turnover rates in the EU's vehicle stock.

Poland represents a notable exception to this trend: between 2016 and 2021, the average lifespan of vehicles in the country declined, even though it still had one of the oldest vehicle fleets in Europe in 2021. This apparent rejuvenation can be linked to a resurgence in both used car imports and new car registrations during this period, especially from 2016 onward. A strong domestic economy, rising incomes, and the growing popularity of leasing contributed to an increase in the number of relatively newer vehicles entering the fleet. As a result, the overall age of the fleet was slightly reduced, despite Poland's long-standing reliance on imported used vehicles from Western Europe (Kolsut, 2020). It is important to note, however, that multiple factors – including national policies, macroeconomic conditions, consumer preferences, and trade dynamics – can influence both import volumes and the age structure of vehicle fleets.

[1] Weighted average calculates the average lifespan considering the vehicle fleet size.

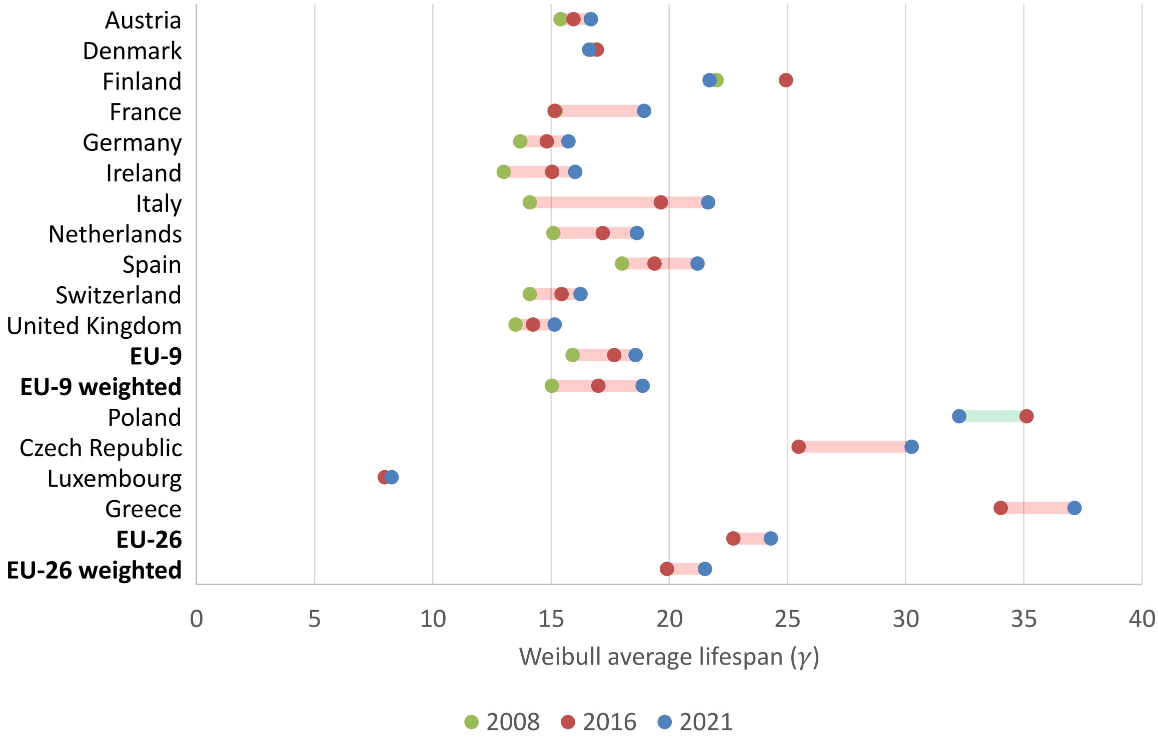

Fig. 4. Temporal variation of the Weibull average lifespan (γ) for 2008, 2016, and 2021 across 11 European countries. For the nine EU countries, we also calculate the average lifespan for the group (EU-9[1]) and a weighted average based on fleet size (EU-9 weighted). Additionally, data for other EU countries is available for 2016 and 2021, including Poland, Czech Republic, Luxembourg, and Greece. The overall EU-26 average and the weighted average for the EU-26 are included as well. In the graph, red highlights indicate an increase in the average lifespan from 2008 to 2021 (when 2008 data is available) or from 2016 to 2021 (when 2008 data is not available). Green indicates a decrease in the average lifespan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Stock model

Before projecting the stock model results up to 2050, the model is validated in a two-step approach (cf. Fig. 5). Model results are compared with actual new BEV registration shares. Firstly, model results are validated using 2021 CSP estimated curves and actual BEV new registrations (EAFO, 2024) (cf. Section 3.2.1 and cf. Fig. 6). Secondly, model results are validated using again 2021 CSP estimated curves and the estimated new BEV registrations from Möring-Martínez et al. (2024) (cf. Section 3.2.2 and cf. Fig. 7).

3.2.1. Validation of the stock model with historical BEV results

The stock model approach, as described in Section 2.3, is first validated by assessing the CSP curves approach. Historical BEV stock shares are compared with those estimated using CSP curves from 2021 and actual new registration shares from 2014 to 2023 (cf. Fig. 6). The estimated results, presented in Fig. 6, are very similar across most analyzed countries. It should be noted that the plots in Fig. 6 use different y-axis scales for each country to better display trends within each national context, especially considering the wide variability in market sizes and BEV shares across countries. This approach can visually exaggerate the differences between modeled and actual shares in smaller markets such as Hungary, Latvia, and Lithuania. While the plots might give an impression of larger errors, the numerical discrepancies remain small in absolute terms, with estimated errors well below 1% (e.g., 0.4% in Hungary in 2022). Therefore, despite the visual impression, the model's forecasting errors are quantitatively minor, as further confirmed by the low RMSE values reported.

To quantify the model's accuracy, we use the average Root Mean Square Error (RMSE), as defined in Domarchi and Cherchi (2023). The average RMSE for the EU-27+Norway from 2014 to 2023 is 0.11%. Additionally, the average RMSE across all 29 territories (28 individual countries plus the EU-27+Norway combined), is 0.15%. This combined average is derived by taking the average RMSE of each territory, providing a broader view of accuracy. This average RMSE is lower than the values reported in Domarchi and Cherchi (2023), although their study focused on forecasting errors rather than backtesting the model accuracy. Nonetheless, the very low RMSE achieved using CSP curves from 2021 suggests that the model's performance can be evaluated as accurate.

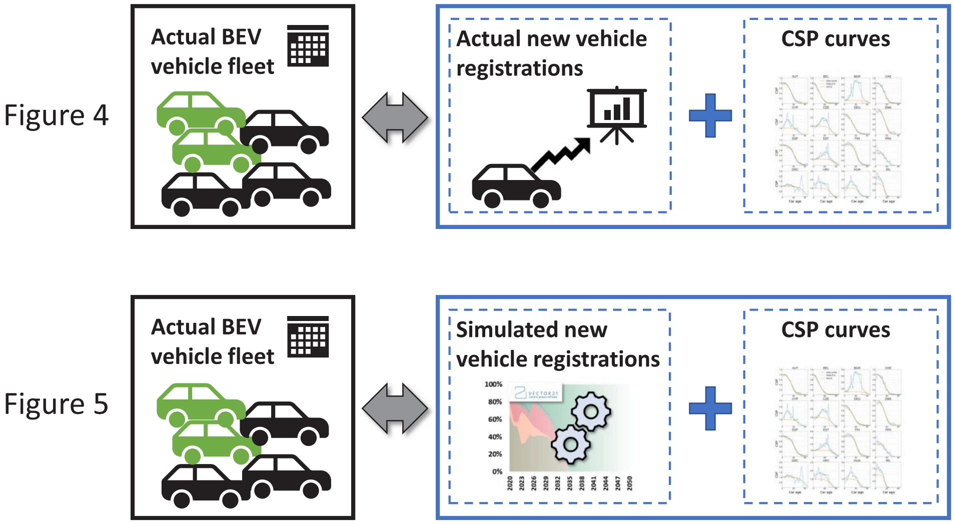

Fig. 5. Two-step stock model validation approach for estimating future BEV stock shares.

3.2.2. *Validation of stock model with clustering approach*

After confirming that CSP curves combined with actual BEV new registrations can accurately estimate historical BEV stock shares, the next step is to evaluate the model's performance using a transportation model that projects future BEV shares. Assuming that CSP curves remain stable over time, this approach is expected to produce reliable scenarios.

For this purpose, we use a transportation model using a clustering approach from Möring-Martínez et al. (2024) for a second validation step. Specifically, we compare historical BEV stock shares from 2014 to 2023 with BEV stock shares estimated using the 2021 CSP curves in combination with the clustering-based transportation model (see Fig. 7).

The results remain broadly consistent across most countries analyzed. However, applying Norway's BEV new registration data to Sweden (both countries are grouped in the same cluster) results in an overestimation of Sweden's BEV stock shares. The average RMSE for the EU-27 plus Norway during this period is 0.18%. While this represents a slight increase compared to the first validation step, the RMSE remains low and continues to outperform models reported in Domarchi and Cherchi (2023). Across all 29 territories (the EU-27 countries, Norway, and EU as a whole), the average RMSE is 0.6%. Despite this modest increase, the error remains acceptably low. Given that prior models in Domarchi and Cherchi (2023) focus on either individual countries or the entire EU, the accuracy achieved using the combination of 2021 CSP curves and the transportation model from Möring-Martínez et al. (2024) can be considered acceptable for predicting future BEV stock shares.

3.2.3. *BEV stock results*

Following model validation, BEV stock shares are projected up to 2050 (cf. Fig. 8). BEVs make up 2% of the EU-27+Norway fleet, based on recent market data (EAFO, 2024). Projections suggest that this share will grow to 3% in 2024 and 5% by 2025, with adoption following an S-shaped curve. By 2030, BEVs are expected to comprise 16% of the fleet, rising to 36% in 2035, 57% in 2040, and 85% by 2050. An 85% BEV share in 2050 would reduce tailpipe emissions substantially, though it may still fall short of the EU's 90% CO_2 reduction target (Comission, 2021) unless either the vehicle miles driven decrease or internal combustion engine vehicles (ICEVs) efficiency improves considerably.

By examining EU countries individually, differences in BEV stock adoption emerge. Luxembourg shows the fastest adoption due to its high turnover rate (see Appendix A). Although Luxembourg and the Netherlands are grouped in the same new vehicle registration adoption cluster (Möring-Martínez et al., 2024) and both are modeled based on the Netherlands' BEV registration shares, Luxembourg's faster turnover results in a projected BEV stock share of 78% by 2030, compared to the Netherlands' 44%. Norway, initially showing higher BEV shares, will see slower growth in the future due to lower turnover rates, reaching a 90% BEV share by 2038, whereas Luxembourg will achieve this milestone by 2033.

France and Germany are projected to reach BEV shares of 46% and 45% by 2035, slightly exceeding the EU-27+Norway average, while Spain and Italy are expected to reach 30% and 29%, slightly below the average. Eastern European countries, such as Poland and Bulgaria, are projected to have the slowest adoption, with BEV shares at 10% and 6% by 2035 and modest increases to 24% and 15% by 2040. These figures suggest minimal progress in electrification, even with the introduction of the ICE ban, as both countries will still fall short of the EU's emissions targets by 2050, with projected BEV shares of 66% for Poland and 51% for Bulgaria.

In absolute numbers, there were approximately 5 million BEVs in the EU-27 and Norway in 2023 (EAFO, 2024). The total is expected to rise to 39 million by 2030, 152 million by 2040, and 249 million by 2050. Although growth is rapid in the early years, it gradually slows each year until 2050. On a country basis (cf. Fig. 9), Germany and France are projected to have the largest number of BEVs on the road by 2030, followed by Sweden, Italy, the Netherlands, and Norway. While Sweden, the Netherlands, and Norway,

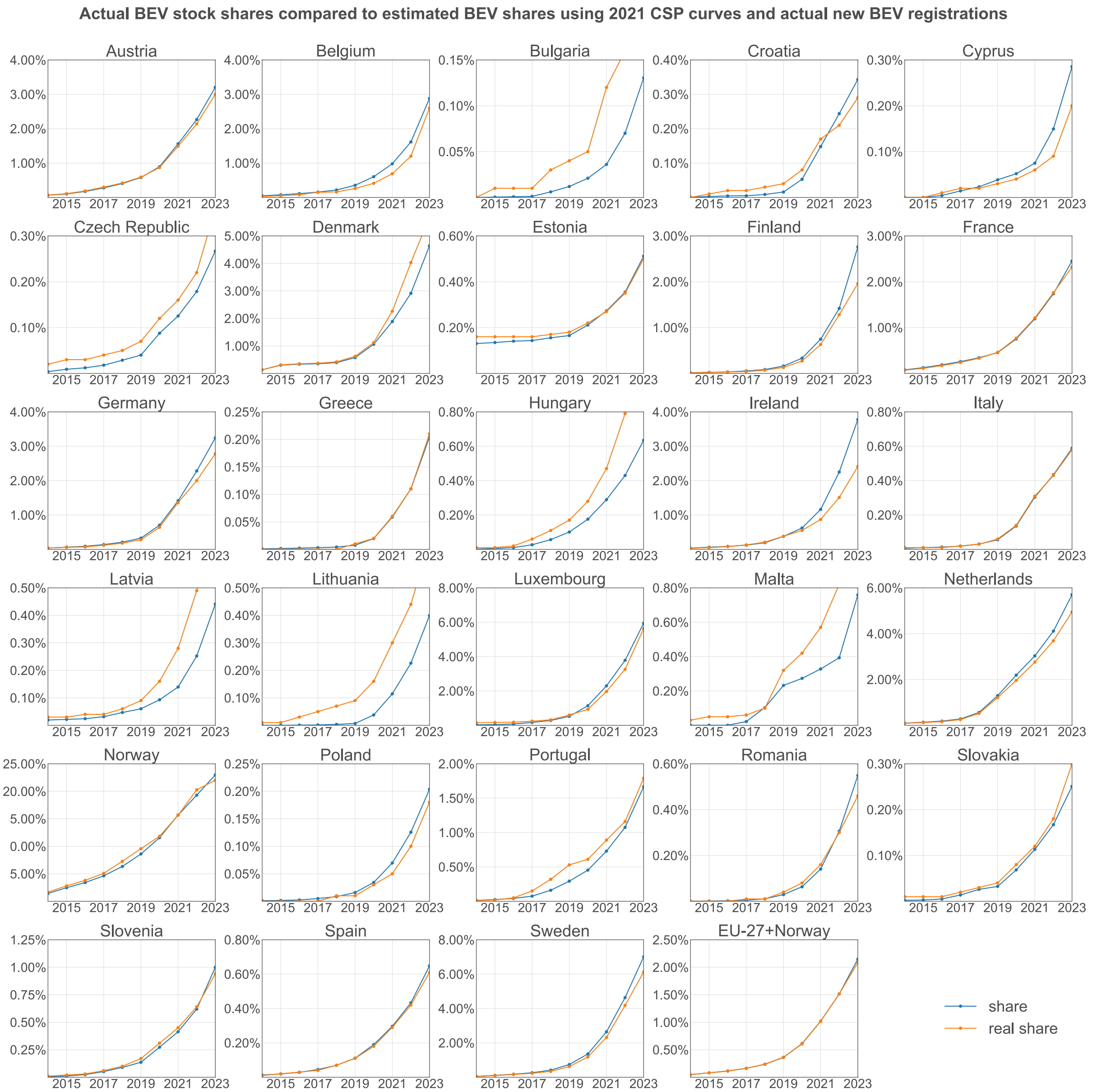

Fig. 6. Comparison of actual BEV stock shares (orange) (EAFO, 2024) with BEV stock shares estimated using 2021 CSP curves (blue), and actual registration data for all EU-27 countries and Norway from 2014 to 2023. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

considered innovator markets, are expected to have BEV shares exceeding 40%, Germany and France are projected to reach only 20% by 2030. Italy ranks fourth in total BEV numbers due to the size of its market, despite having a BEV share of just 10%.

By 2040, Germany, France, Italy, Spain, and Poland are projected to have the highest number of BEVs on the road. While the BEV share is expected to reach around 50% in Italy and Spain, and about 25% in Poland, these percentages are still lower than in countries like the Netherlands, Sweden, and Norway, where BEV shares are projected to exceed 90%. Despite this, Italy, Spain, and Poland will have more BEVs in absolute terms due to their larger overall vehicle fleets.

By 2050, the top five countries with the largest BEV fleets are expected to remain Germany, France, Italy, Poland, and Spain. Germany and France are projected to have BEV stock shares exceeding 90%, while Italy and Spain will reach over 80%. The Czech Republic and Romania are projected to become the 7th and 8th largest BEV markets, with over 5 million BEVs each and a 60% market share. By 2050, 12 countries are expected to have BEV shares exceeding 90%, while 17 will surpass 80%, and the remaining 11 will reach above 50%. Nonetheless, 16 EU countries are projected to fall short of a 90% BEV stock share by 2050. Reaching the

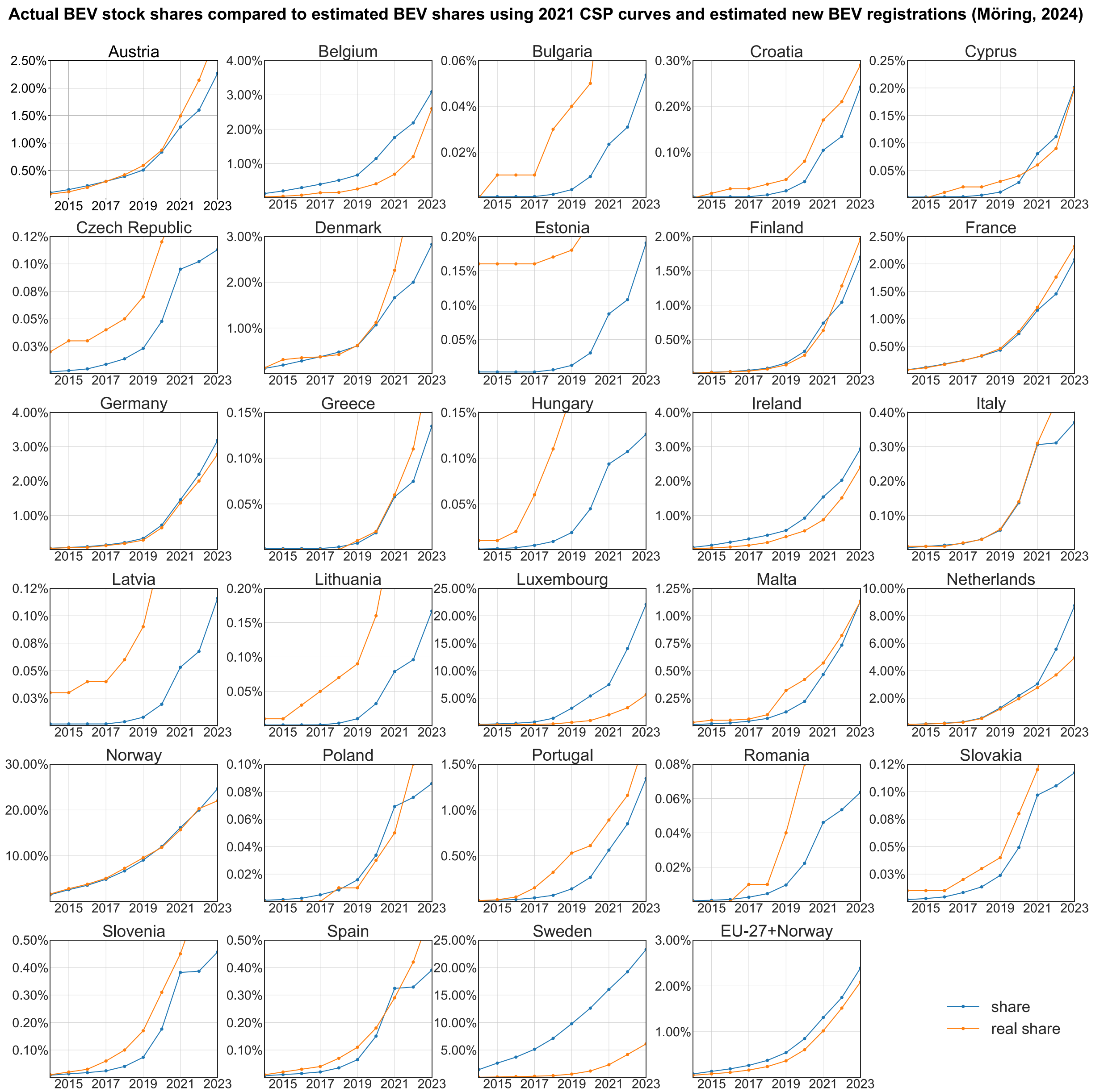

Fig. 7. Comparison of actual BEV stock shares (orange) (EAFO, 2024) with BEV stock shares estimated using 2021 CSP curves and a clustering-based transportation model (blue) from Möring-Martínez et al. (2024) for EU country clusters from 2014 to 2023. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

EU's 90% emissions reduction target will likely require additional measures across the region, especially if travel demand remains high or increases, ICEVs do not significantly reduce emissions, or other emission-reduction strategies are not widely implemented.

While the ICE ban will drive fleet electrification, the transition may require more years than desired with current vehicle turnover rates. Additional policies, such as scrappage schemes, may be necessary to accelerate the replacement of older vehicles and ensure sufficient progress towards emission targets.

3.3. Sensitivity analysis

Given the variation in average vehicle lifespan across countries – shaped by differing socioeconomic conditions – and its evolution over time, it is essential to assess how changes in cumulative survival probability (CSP) curves affect overall stock dynamics and emissions trajectories. After validating the stock model with historical results and examining projections under the reference scenario, sensitivity analysis is conducted to evaluate the robustness of model outcomes under alternative fleet turnover

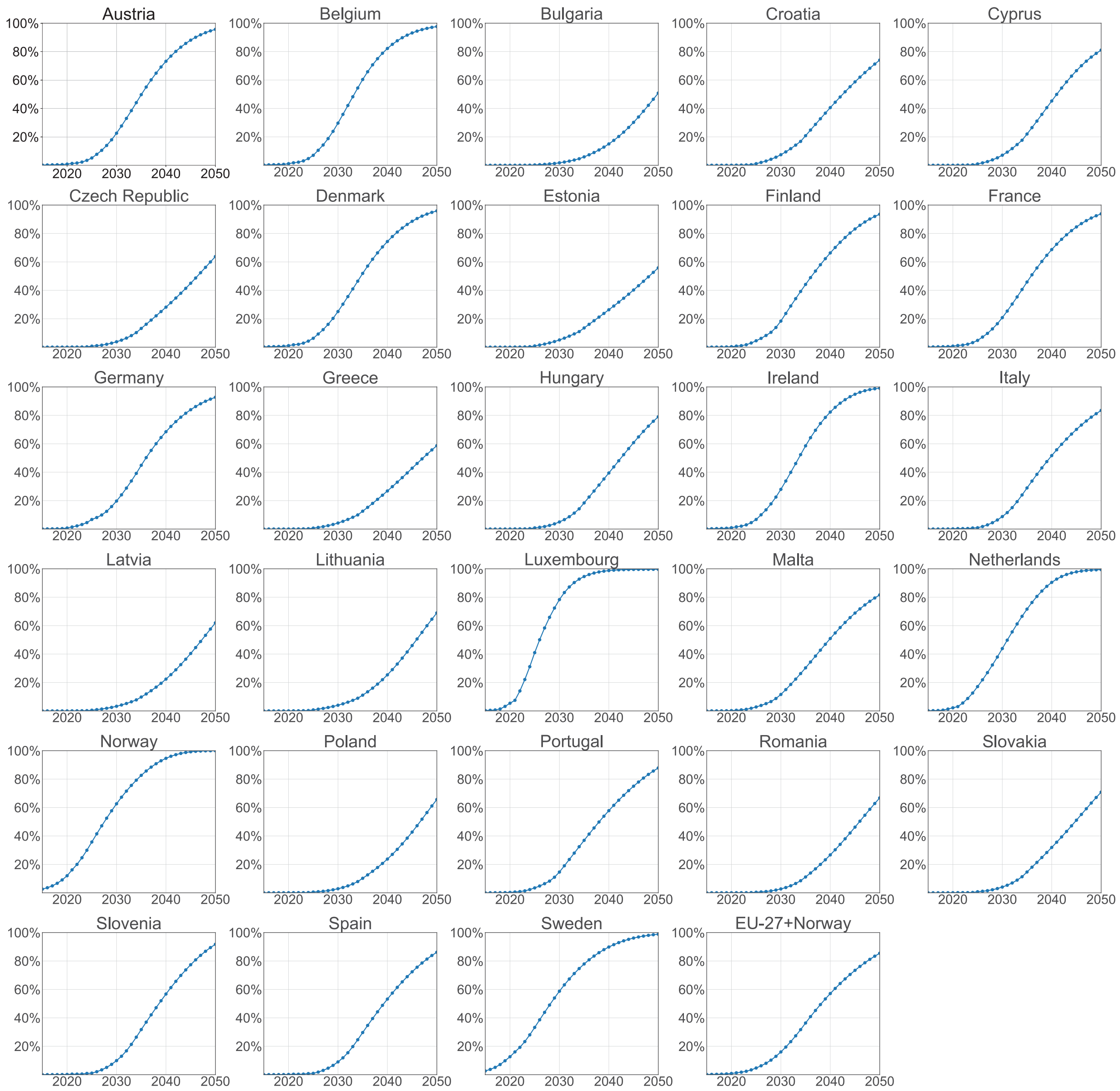

Fig. 8. Estimated BEV stock shares for EU-27+Norway up to 2050.

scenarios. This approach helps identify which assumptions have the greatest influence on electrification pathways and, by extension, decarbonization timelines. Such analysis is especially important in the absence of consistent data on scrappage policies or cross-border flows of used vehicles, and it underscores the critical role of fleet turnover rates in determining the pace of fleet electrification in the European passenger car sector.

3.3.1. Effect of different country CSP curves

In 2021, the average age of vehicle fleets across Europe ranged from 6.2 years in Luxembourg to 19.5 years in Bulgaria. The country-specific CSP curves significantly affect the BEV stock shares, and this Section presents a theoretical exercise where the CSP curves of countries like Bulgaria and Luxembourg are applied to all EU countries to observe their impact on BEV stock shares (see Fig. 10). Assuming all other factors remain constant, including the estimated new BEV registrations for each country, the country CSPs are varied to assess their influence. The results highlight the importance of stock fleet turnover rates.

For example, in the EU-27+Norway, a BEV stock share of 57% is estimated for 2040 using actual country CSPs. However, if all European countries adopted Bulgaria's CSP, the BEV fleet share in 2040 would drop to 20%, even with the current high levels of

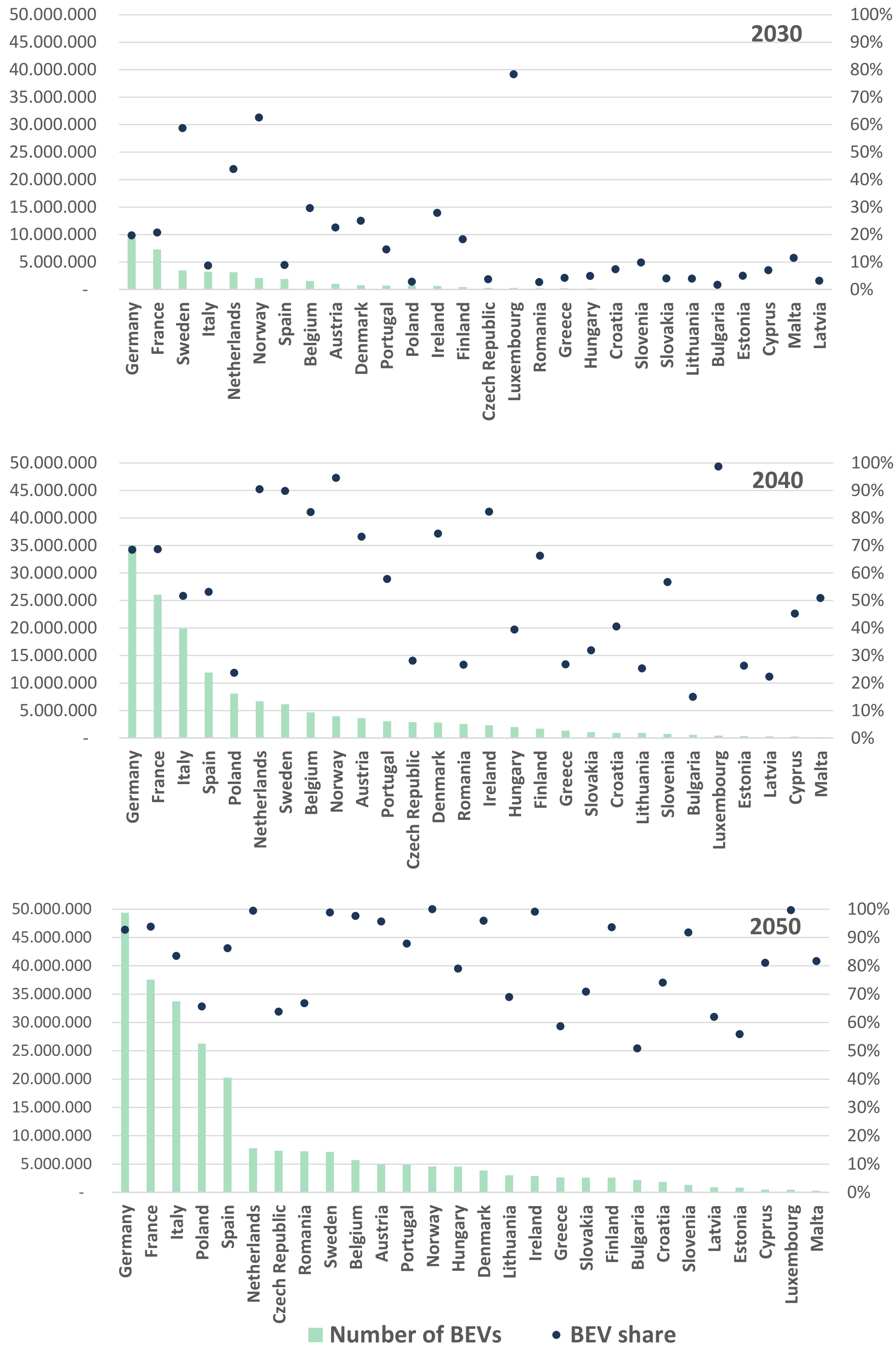

Fig. 9. Estimated absolute numbers of BEV on the road as well as the BEV share for EU-27 countries+Norway in 2030, 2040 and 2050.

BEV sales, the CO_2 emission targets, and the zero-emission new vehicle registrations mandated from 2035 onwards. Conversely, if all European countries adopted Luxembourg's CSP turnover rates, the BEV fleet share would increase to 89% by 2040.

Countries with high levels of used vehicle imports, such as Bulgaria, Poland, and the Czech Republic, would significantly increase their BEV stock shares if they had stock turnover rates similar to those in Western Europe. For instance, Poland's BEV stock share is expected to be 24% in 2040, but with Germany's CSP, it could rise to 58%. Similarly, countries like Germany and France, which have low levels of used car imports and relatively fast turnover rates compared to other EU countries, are expected to achieve close to a 70% BEV stock share by 2040. If Luxembourg's turnover rates were applied to these countries, they could reach around 90%.

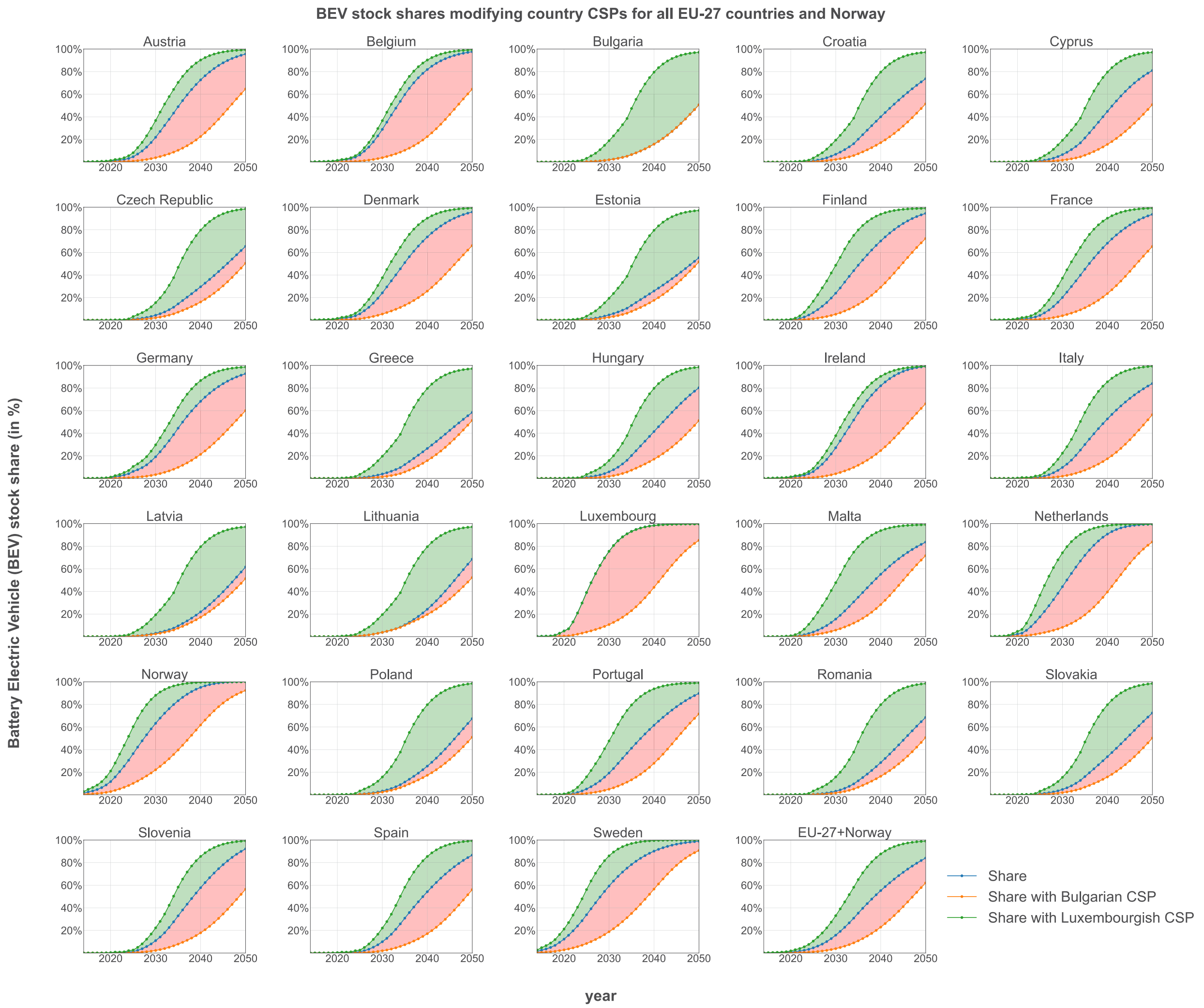

Fig. 10. BEV stock shares using different country CSPs for all EU-27 countries and Norway. Own country CSP is used, also Bulgarian, and Luxembourgish CSP; are used for all countries. The green colored area represents the BEV share increase when using a different country CSP than the real one, and the red colored area represents a decrease in BEV share. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These sensitivity analyzes demonstrate the critical role of fleet turnover rates in achieving decarbonization targets. While it is clear that survival rates are influenced by various economic and social factors, and it is unrealistic to expect countries like Bulgaria to achieve the same turnover rates as Luxembourg, the analysis suggests that the negative trends in fleet electrification could be reversed with proactive government policies. For example, policies that promote vehicle scrapping and faster fleet renewal could accelerate the transition to electric vehicles.

3.3.2. Effect of historical temporal variation of CSP curves

As previously observed, the average lifespan of passenger cars has increased in most countries since 2008. Here, we analyze the impact of maintaining the substitution dynamics (CSP curves) from 2008 and 2016, and compare it with the current stock fleet turnover rates using 2021 CSP curves (cf. Fig. 11). In the EU-9, data is available for the years 2008, 2016, and 2021. During this period, the average lifespan has consistently increased (cf. Section 3.1). The Weibull average lifespan, γ, increased from 15 years to 18.9 years, representing an increase of 26%. If the 2008 turnover rates were applied, the BEV stock share in 2030 would be 22%; however, with the current 2021 turnover rates, the share is projected to be 17%. The difference becomes more pronounced by 2040, where the BEV stock share would be 76% with the 2008 rates, compared to 64% with the 2021 rates. By 2050, a 98% BEV share could be reached using the 2008 CSP curves, whereas only 90% is expected with the current rates. On average, between 2025 and 2050, the BEV share is 8 percentage points lower under the current turnover rates, which has a significant impact on CO_2 emissions.

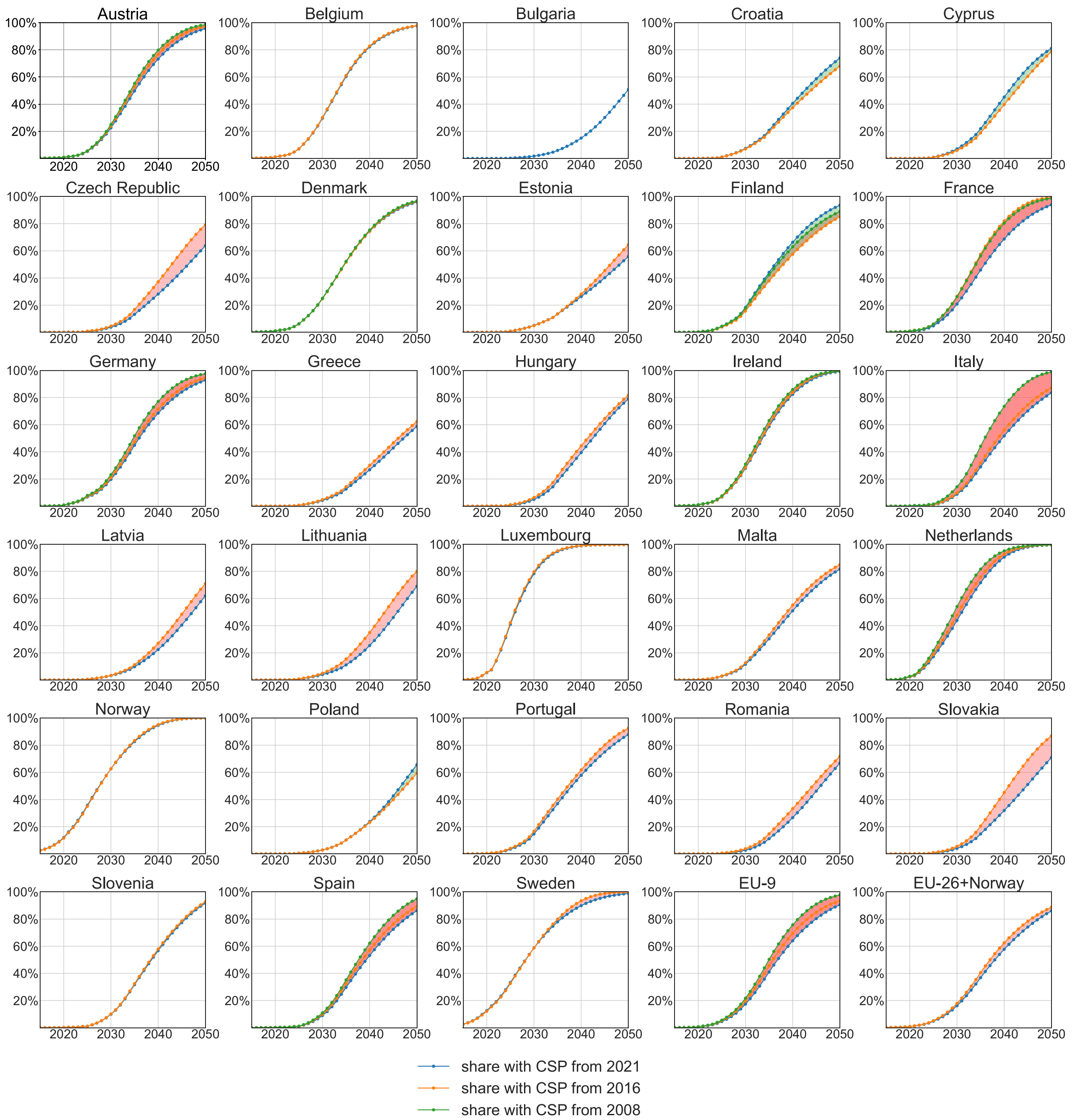

Fig. 11. BEV stock shares using empirical CSP curves from 2008, 2016 and 2021 for all EU-27 countries and Norway. The green colored area represents the BEV share increase when using 2021 CSP curves compared to 2008 or 2016 CSP curves, and the red colored area represents a decrease in BEV share. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Beyond the EU-9, similar trends are observed for the EU-26+Norway when comparing stock turnover rates from 2016 to the current rates from 2021. In 2030, the BEV share would be 18% with the 2016 rates, compared to 16% with the 2021 rates. By 2040, the BEV share is projected to be 63% under the 2016 rates, whereas it would be 58% with the current rates. In 2050, the share would reach 89% using the 2016 rates, versus 86% with the 2021 rates. Overall, from 2025 to 2050, the BEV share is 3 percentage points lower with the current turnover rates compared to those from 2016.

A longer vehicle lifespan directly impacts overall CO_2 emissions, which are lower under the assumed CSP curve from 2008. Over the past 15 years, there has been a noticeable shift towards longer vehicle lifetimes. If this trend continues, it could have a further dampening effect on the electrification rate of the European vehicle fleet. To counteract this trend, governments can introduce scrappage schemes, similar to those implemented in various European Union countries in 2008 (Marin and Zoboli, 2020; Svoboda et al., 2023). By doing so, they would not only benefit their own markets but also have a positive impact across the entire European market, as fewer older vehicles would be available for resale within the region. This would accelerate the transition to a less CO_2 emission-intensive fleet.

However, scrappage schemes have shown limited effectiveness in reducing CO_2 emissions and may even increase emissions when considered on a life-cycle basis (Brand et al., 2013; Grigolon et al., 2016; Fraga, 2011). Greater CO_2 reduction could be achieved if the replacement of old vehicles was limited to hybrid electric vehicles (HEVs) (Kagawa et al., 2013). Moreover, life-cycle assessments of different powertrains in Spain, France, and the EU (Puig-Samper Naranjo et al., 2021; Ternel et al., 2021) suggest that replacing old vehicles with BEVs would result in even greater emission reductions than with HEVs. As the electrical grid becomes cleaner, the potential for emission reductions with BEVs will further increase.

3.3.3. Effect of increase and decrease of stock fleet average age

In the previous analysis, we analyze the future BEV stock shares using different historical CSP (car stock profile) curves. In this analysis, we focus on the effects of modifying the average age of the vehicle fleet across different levels for each country and the EU as a whole (cf. Fig. 12). To achieve this, we adjust the Weibull average lifespan, γ, and for high-importing countries, we also modify the normal Gaussian distribution, μ.

The average vehicle age may increase if the mass adoption of EVs is slower than anticipated. This could result from a variety of factors, including technological and psychological barriers such as a lag in consumer acceptance, or other reasons that persist even after the ban on ICEVs. These factors could lead to a scenario where older vehicles remain in use for longer periods, thereby delaying the overall fleet electrification.

Assuming the average vehicle age continues to increase at a rate similar to that observed from 2008 to 2021, there would be an increase of approximately 20% in the average vehicle age by 2035. Under this scenario, the BEV stock share in the EU would reach around 31% in 2035, compared to 36% if the fleet turnover rate remained unchanged. Conversely, if vehicle scrappage schemes were implemented across the EU in the coming years, bringing stock fleet turnover rates back to 2008 levels, the average vehicle age could decrease by about 20%. In this case, the BEV stock share could reach approximately 44%.

The average vehicle age significantly influences the rate of electrification of the vehicle fleet. By 2050, assuming current turnover rates, an estimated 85% of the fleet is likely to be BEVs. However, if the average vehicle age increases by 20%, BEV penetration would decrease to around 78%. Conversely, if the average vehicle age is reduced by 20%, the BEV stock share could increase to nearly 92%.

3.3.4. Effect of different country BEV new registration shares

After analyzing the impact of modifying stock fleet turnover rates on future BEV stock shares, we now examine the effect of varying annual BEV new registration shares. Specifically, we assess the outcomes if EU member states were to adopt the simulated BEV new registration shares of countries like Norway, Poland, or France.

Our findings indicate that, under current EU regulations, stock fleet turnover rates have a significantly greater influence on BEV stock share than do BEV new registration shares. For example, in the Czech Republic, the BEV stock share is projected to reach 28% by 2040. If the Czech Republic adopted Norway's BEV new registration rates (the highest in the EU) starting in 2024, the BEV stock share would increase to 57%. However, if the Czech Republic adopted Luxembourg's CSP (car stock profile) turnover rates, the highest in the EU, the BEV stock share could reach 81% (cf. Fig. 10).

Similarly, Austria's BEV stock share is expected to be 73% by 2040. With Luxembourg's turnover rates, it could rise to 92%, while adopting Bulgaria's rates could reduce it to 22%. If Austria matched Norway's BEV sales rates, the share could reach 89%; with Poland's sales rates, it would be 56%. The Austrian results shows that altering turnover rates could increase the BEV stock share by up to 19 percentage points or decrease it by up to 51 percentage points (a range of 71 percentage points total). In contrast, changes in BEV new registration rates could increase the stock share by up to 16 percentage points or decrease it by the same amount (a total range of 32 percentage points).

Given the 2035 mandate for transitioning to only zero-emission vehicle new registrations, the rate of replacing older vehicles (stock fleet turnover rates) has a more substantial impact on achieving a highly electrified fleet in the next decade than the rate of new BEV sales.

4. Limitations

This paper uses country-specific survival rates, assuming that cumulative survival probability (CSP) rates do not change across powertrain types and vehicle segments due to limited data availability across all EU countries. In other words, a single survival rate is applied across all powertrain types in the model. While this was a reasonable simplification in earlier years due to limited data, recent research Nguyen-Tien et al. (2025) shows that newer BEVs now reach lifespans comparable to ICEVs, even under more intensive use. This supports the assumption of similar survival rates but highlights the need for continued monitoring as the BEV fleet ages. Furthermore, if BEV prices remain high and consumer acceptance does not increase following the 2035 ICE ban, it is unclear whether gasoline vehicles will be scrapped or exported at today's rates.

The CSP curves used are empirical estimates from 2008, 2016 and 2021 and may not reflect future scrappage rates precisely. In the reference scenario, CSP rates are assumed to stay constant over time; however, we examine scenarios with both lower and higher CSPs to evaluate potential impacts.

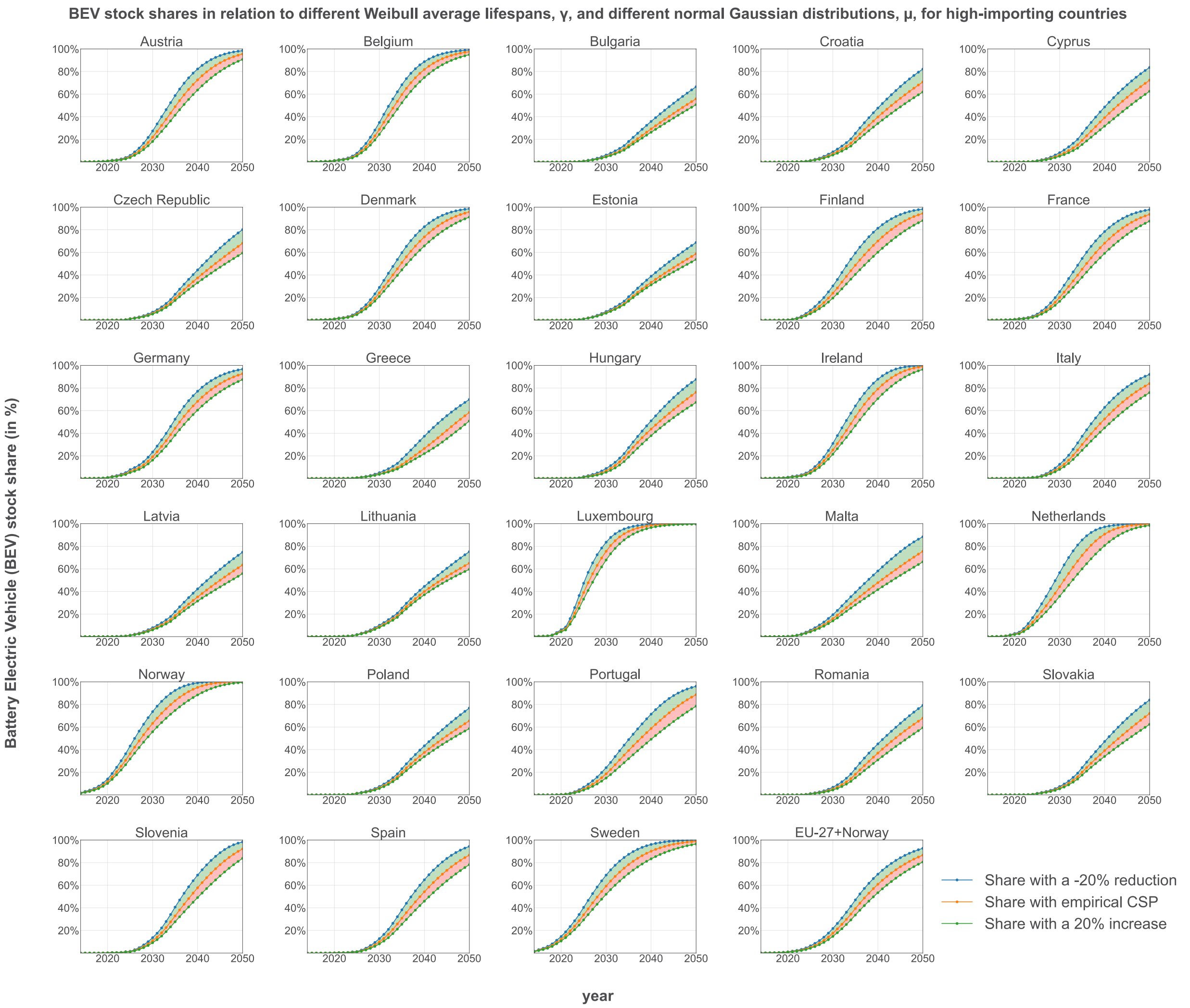

Fig. 12. BEV stock shares in relation to different Weibull average lifespans, γ, and different normal Gaussian distributions, μ, for high-importing countries. A vehicle lifespan increase of 20% as well as a reduction of 20% is applied to both parameters. This adjustment results in an average age increase of 19% and a reduction of 19% across all countries. The green-colored area represents the increase in BEV share when the average age is reduced, while the red-colored area represents the decrease in BEV share when the average age is increased. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Finally, transportation models may contain estimation errors. For example, the model by Möring-Martínez et al. (2024) overestimates BEV registration shares in the Netherlands for 2023–2025, leading to a higher projected BEV stock share in this paper. Moreover, the model clusters certain countries, such as Sweden and Norway, which differ significantly in BEV shares. These factors can lead to over-or underestimation for specific countries. This limitation can be overcome using multiple transportation model scenarios (when available) and comparing results to obtain a more robust projection of future fleet composition.

5. Conclusions

Achieving a 90% BEV stock share in the EU by 2050 will require additional measures beyond current policies. Our findings align with Plötz et al. (2023), showing that current EU policies fall short of the targets set by the Paris Agreement and the EU's goal of a 90% reduction in GHG emissions. To address this, we developed a modular methodology that combines a bottom-up transportation model for new BEV registrations (Möring-Martínez et al., 2024) with a country-specific model based on survival rates (Held et al., 2021), allowing projections of future fleet composition under various scenarios.

Survival rates have changed significantly over time in EU countries. This paper updates the cumulative survival probability (CSP) curves for all EU member states up to 2021. Our study shows a consistent increase in vehicle lifespan across the EU, with EU-9 countries seeing over a 10% rise between 2008 and 2016, and between 2016 and 2021. This trend, which is reflected in updated cumulative survival probability (CSP) curves, contributes significantly to delayed fleet turnover. As older vehicles remain in circulation longer, they inhibit rapid BEV integration. Under our reference scenario, BEV stock in the EU-27 and Norway is projected to reach 85% by 2050. While this level substantially reduces tailpipe emissions, it still falls short of the EU's 90% GHG reduction target, suggesting that further emissions reduction strategies, such as reduced mileage or scrappage schemes, will be required.

Electrification pathways vary notably among EU countries, with projected BEV stock shares ranging from 51% in Bulgaria to over 90% in twelve EU countries by 2050. BEV stock is expected to grow significantly across the EU-27 and Norway – from 5 million in 2023 (EAFO, 2024) to 249 million by 2050 – demonstrating exponential growth up to 2040 and moderate growth thereafter. Differences in BEV adoption across countries arise from both new BEV registration rates and fleet turnover rates (CSP curves). Sensitivity analyzes show that turnover rates have a greater impact on BEV stock than new registrations. For example, the projected 2040 BEV share in the EU-27 and Norway would be 57% based on current turnover rates, but could drop to 20% if all countries adopted Bulgaria's lower rates, or increase to 89% with Luxembourg's faster rates. While it may be unrealistic for countries like Bulgaria to match Luxembourg's rates due to economic and social factors, policies promoting scrapping and faster fleet renewal could still significantly accelerate BEV adoption across Europe.

The increasing average age of EU passenger vehicles, from 15 years in 2008 to 18.9 years in 2021, poses a barrier to BEV adoption. For instance, if the EU-9 fleet had 2008 stock turnover rates, the BEV share could increase by 8 percentage points by 2050, reaching 98% instead of 90%. In the EU-26 plus Norway, having 2016 turnover rates rather than 2021 rates would raise the projected BEV share in 2050 from 86% to 89%. Prolonged vehicle lifespans slow electrification and hinder CO_2 emission reduction unless offset by scrappage schemes, which are most effective when replacing old vehicles with HEVs or BEVs, with BEVs offering the greatest emissions benefits.

The impact of vehicle lifespan further illustrates the importance of turnover trends. If the EU vehicle fleet age continues to increase at the same pace as between 2008 and 2021 and rises a 20% by 2035, the BEV stock share would drop from 36% to 31%. Conversely, reducing fleet age by 20% to 2008 levels through an EU-wide scrappage program could increase the BEV share to 44% in 2035. By 2050, BEV stock would reach 85% with current turnover rates, but this share could decrease to 78% if aging persists or rise to 92% with a reduced average age. This analysis highlights that the aging of the fleet could make a difference of more than 10% in 2035 and 14% in 2050 depending on whether turnover rates are accelerated or slowed.

In summary, this paper highlights that while increasing BEV new registrations is important, accelerating vehicle turnover rates is a more powerful driver of long-term BEV adoption across the EU. Our analysis shows that effective decarbonization will depend on both EU-wide and member-state actions to influence turnover dynamics, especially with the 2035 ICE ban approaching. This paper offers a framework for understanding and examining how turnover rates influence BEV adoption, suggesting that targeted policies to reduce fleet age could greatly accelerate progress towards the EU's 2050 decarbonization goals and bring the EU closer to its 2050 climate goals.

6. Further work

The model can be used to evaluate the effects of different transportation scenarios, enabling an analysis of how various policies and market conditions might impact BEV stock shares and emissions. Scenarios could include higher taxation on combustion engine vehicles, scenarios where battery price reductions are lower than expected, and scenarios where the 2035 ICE ban is delayed or not implemented. Using the model to simulate these scenarios provides insights into how each factor could affect decarbonization, fleet turnover, and progress towardss EU emissions targets.

The model can be extended to estimate greenhouse gas (GHG) emissions and assess the Europe's progress towards the Paris Agreement targets, particularly focusing on the EU's 90% emissions reduction goal and the contributions of individual countries. This extension would require incorporating emission factors from INFRAS (2022) and annual mileage data, enhancing the model's capability to evaluate both regional and national progress towards decarbonization targets.

Additionally, the model could simulate the impact of different scrappage schemes on BEV stock shares, offering insights into how these schemes might accelerate fleet electrification for a faster transition to low-emission transportation. Evaluations of past scrappage schemes across the EU, such as those by Svoboda et al. (2023), show different levels of effectiveness. Drawing on successful examples, the model could assess the potential outcomes of future scrappage schemes to support optimized decarbonization strategies within the EU.

CRediT authorship contribution statement

Gabriel Möring-Martínez: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Murat Senzeybek:** Writing – review & editing, Methodology. **Samuel Hasselwander:** Writing – review & editing, Visualization. **Stephan Schmid:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Data and code statement

The data and code used in this study are openly available in the repository cited by Möring-Martínez (2025).

Declaration of competing interest

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

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Appendix A. CSP curves (2021)

A.1. Vehicle stock data

To compute the cumulative survival probability of cars, age-resolved stock data is required. We use the same data sources as Held et al. (2021): the European Automobile Manufacturers' Association (ACEA), the United Nations Economic Commission for Europe (UNECE), and national statistics (NatStat). The data availability and resolution are summarized in Table A.1. For this study, NatStat data is selected for all countries because it has the highest resolution. Specifically, 15 out of 32 countries provide full resolution for cars up to 45 years and older, 9 countries provide yearly resolution up to 20 years, and 8 countries have lower resolutions. This resolution is comparable to that reported by Held et al. (2021).

National statistics (NatStat) has been individually gathered from national statistics offices, ministries of interior or transport, national automotive associations, national automotive companies, and others. If 2021 age-resolved stock data was unavailable, data from 2020 or 2022 is used, assuming minimal yearly variation in age distribution as confirmed by Oguchi and Fuse (2015) and Held et al. (2021).

A.2. New registration data

In addition to vehicle stock data, the computation of survival probabilities also requires knowledge on the number of new vehicle registrations per year. Data gathered from Held et al. (2021) until 2016 is used and registrations between 2017 and 2021 are included verifying the homogeneity with previous years. Two different data sources have been considered in this study for updating the numbers: the European Automobile Manufacturers' Association (ACEA), and national statistics (NatStat). The data sources for the period 2017–2021 are summarized in Table A.2.

A.3. CSP estimation with 2021 data

The empirical CSP data of 2021 is calculated using Eq. (2) and using the methodology by Held et al. (2021), the data can be fitted by Weibull (cf. Eq. (3)) and Weibull-Gaussian curves (cf. Eq. (4)) for all 32 countries (cf. Fig. A.1 and Fig. A.2). The corresponding fitting parameters and the optimum distribution are documented in Table A.3. As in 2016, in 2021 fitting a Weibull curve to countries with a high number of imported used cars results again in poor R^2 values. Adding the Gaussian curves improves the goodness of fit significantly. The mean R^2 increases from 0.68 to 0.90. While the upper half of the R^2 distribution (>50th percentile) is largely unaffected, the lower half is drastically improved (cf. Fig. A.3).

A.4. Temporal variation of Weibull average lifespan and average age of the stock fleet

The temporal variation can be measured both using the average age and the Weibull average lifespan (γ) fitting parameter. We obtain a high correlation between these two terms, an R^2 of 0.87 (cf. Fig. A.4).

The Weibull average lifespan variation between 2016 and 2021 can be estimated for all countries except for Bulgaria where there is only data available for 2021 (cf. Fig. A.5).

It can be observed that only 7 out of 31 countries where there is data available in 2016 and 2021 experienced a reduction in the average lifespan during this period (cf. Fig. A.5). We can observe that all the rest of countries experienced an increase and also the EU-26 as a whole.

Finally, for analyzing the temporal variation we can also show the average age between 2016 and 2021. It can be estimated for all countries except for Bulgaria where there is only data available for 2021 (cf. Fig. A.6).

Similarly to the average lifespan (cf. Fig. A.5), it can be observed that only 6 out of 31 countries experienced a reduction in the average age during this period (cf. Fig. A.6). This was expected due to the high correlation between the fitting parameter average lifespan and the average age (cf. Fig. A.4).

Appendix B. Supplementary data

The data and code used in this study are openly available at Zenodo (Möring-Martínez, 2025). They contain all scripts and datasets needed to reproduce the analysis presented in this paper.

Table A.1
Age-resolved stock data: Data from national statistics (NatStat) come from national statistics offices, ministries of interior or transport, national automotive associations, national automotive companies, etc. Age bins with aggregate numbers for multiple years are indicated by squared brackets.
Abbreviations: NatStat = National Statistics.

	NatStat (age bins)	NatStat (year)	NatStat (ref)
Austria (AUT)	(1–24, 25+)	2021 (31/12)	Statistik Austria (2022)
Belgium (BEL)	(1–120)	2021 (31/12)	FEBIAC (2022)
Bulgaria (BGR)	([1–5], [6–10], [11–15], [16–20], 21+)	2022 (1/5)	Open Data BG. (2022)
Switzerland (CHE)	(1–7, [8–12], [13–17], [18–22], [23–32], [33–42], [43–62], 63+)	2021 (30/9)	FSO Switzerland (2022a)
Cyprus (CYP)	(1–5, [6–10], [11–15], [16-20], [21–25], 26+)	2021 (31/12)	Cystat (2022)
Czech Republic (CZE)	(1, [2–3], [4–5], [6–10], [11–15], 16+)	2020 (31/12)	SDA (2022)
Germany (DEU)	(1–38, 39+)	2021 (31/12)	Kraftfahrt-Bundesamt (2022)
Denmark (DNK)	(1–25, 26+)	2021 (31/12)	Statistics Denmark (2022)
Spain (ESP)	(1–120)	2021 (31/12)	DGT (2022)
Estonia (EST)	(1–120)	2021 (31/12)	Transpordiamet (2022)
Finland (FIN)	(1–120)	2021 (31/12)	Tilastokeskus (2022b)
France (FRA)	([1–4], [5–9], [10–14], [15–19], [20–24], 25+)	2021 (31/12)	SDES (2022a)
United Kingdom (UK)	(1–120)	2021 (31/12)	gov.uk (2022)
Greece (GRC)	(1–10, 11+)	2020 (31/12)	Hellenic Statistical Republic (2022)
Croatia (HRV)	(1–21, [22–31], 32+)	2021 (31/12)	Center for Vehicles of Croatia (2022)
Hungary (HUN)	(1–120)	2021 (31/12)	KSH (2022)
Ireland (IRL)	(1–22, 23+)	2021 (31/12)	Central Statistics office (2022)
Iceland (ISL)	(1–120)	2021 (31/12)	Samgöngustofa (2022)
Italy (ITA)	(1–20, 21+)	2021 (31/12)	ACI (2022)
Liechtenstein (LIE)	(1–62, 63+)	2021 (31/12)	LLV (2022b)
Lithuania (LIT)	(1–120)	2022 (31/12)	Regitra (2022)
Luxembourg (LUX)	(1–120)	2021 (31/12)	Luxembourg (2022)
Latvia (LAT)	(1–120)	2021 (31/12)	Official Statistics of Latvia (2022)
Malta (MLT)	(1, [2–4], [5–9], [10–19], [20–29], [30–39], [40–49], [50–59], [60–69], 70+)	2020 (31/12)	National Statistics Office (2022)
Netherlands (NLD)	(1–120)	2021 (31/12)	CBS (2022)
Norway (NOR)	(1–120)	2021 (31/12)	SSB (2022)
Poland (POL)	(1–40, 41+)	2021 (31/12)	PZPM (2022a)
Portugal (PRT)	(1–61, 62+)	2021 (31/12)	INE Portugal (2022)
Romania (ROU)	([1–2], [3–5], [6–10], [11–20], 21+)	2021 (31/12)	INS Romania (2022)
Slovakia (SVK)	(1–120)	2022 (31/12)	Ministry of Slovak Republic (2022)
Slovenia (SVN)	(1–25, 26+)	2021 (31/12)	SiStat (2022b)
Sweden (SWE)	(1–19, 20+)	2021 (31/12)	Official Statistics of Sweden (2022)

Table A.2
New registration data between 2017 and 2021 from ACEA and NatStat. Data from NatStat come from national statistics offices, ministries of interior or transport, national automotive associations, national automotive companies, etc.
Abbreviations: ACEA = European Automobile Manufacturers' Association, NatStat = National Statistics.

	NatStat (ref) or ACEA
Austria	Statistik Austria (2023)
Belgium[a]	FEBIAC (2023)
Bulgaria	ACEA (2022a)
Switzerland	FSO Switzerland (2022b)
Cyprus	Cystat (2023)
Czech Republic	SDA (2023)
Germany	KBA (2022)
Denmark	Statistics Denmark (2023)
Spain	Expansión (2022)
Estonia	Statistics Estonia (2022)
Finland	Tilastokeskus (2022a)
France	SDES (2022b)
United Kingdom[b]	gov.uk (2023)
Greece	Statistics Greece (2022)

(*continued on next page*)

Table A.2 (*continued*).

	NatStat (ref) or ACEA
Croatia	ACEA (2022a)
Hungary	ACEA (2022a)
Ireland	CSO (2022)
Iceland	ACEA (2022a)
Italy	ANFIA (2022)
Liechtenstein	LLV (2022a)
Lithuania	ACEA (2022a)
Luxembourg	Statistics Luxembourg (2022)
Latvia	Official statistics Latvia (2022)
Malta	National Statistics Office (2023)
Netherlands	ACEA (2022a)
Norway	ACEA (2022a)
Poland	PZPM (2022b)
Portugal	ACEA (2022a)
Romania	INS Romania (2023)
Slovakia	Ministry of Slovak Republic (2023)
Slovenia	SiStat (2022a)
Sweden	ACEA (2022a)

[a] Data for Belgium is used from 1991 to 2021. The data from Held et al. (2021) does not match the data from *Natstat*.
[b] Data for UK is used from 1970 to 2021. The data from Held et al. (2021) does not match the data from *Natstat*.

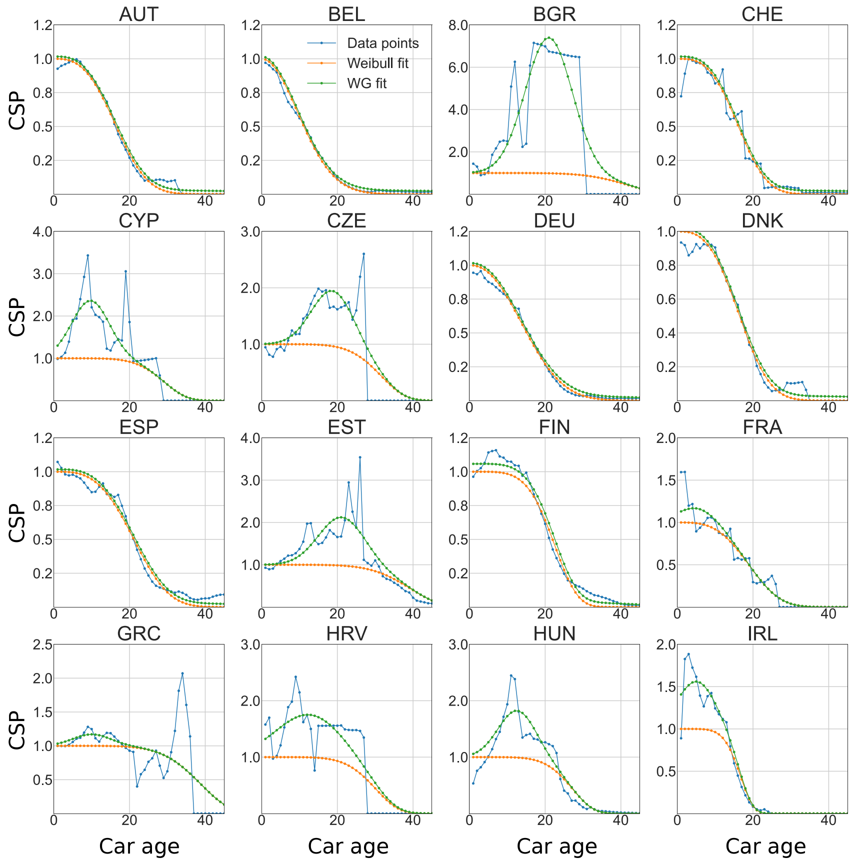

Fig. A.1. Cumulative survival probability (CSP) data in 2021 for European countries (1/2). A Weibull curve (orange) and the sum of a Weibull and a Gaussian curve (green) are fitted to the data (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: The methodology is extracted from Held et al. (2021).

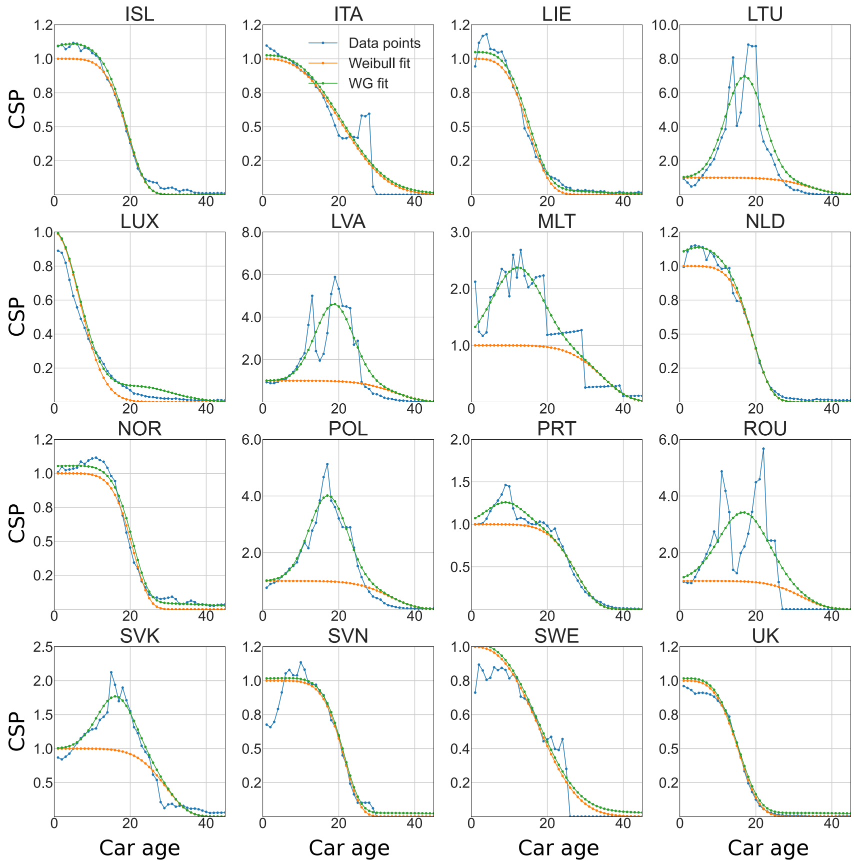

Fig. A.2. Cumulative survival probability (CSP) data in 2021 for European countries (2/2). A Weibull curve (orange) and the sum of a Weibull and a Gaussian curve (green) are fitted to the data (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: The methodology is extracted from Held et al. (2021).

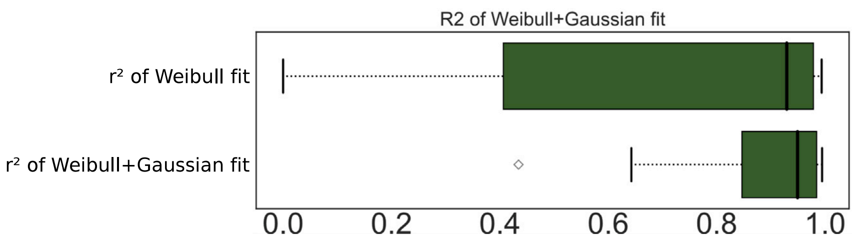

Fig. A.3. Boxplots of the R^2 values from a Weibull curve and from the sum of a Weibull and a Gaussian curve. The box represents the median and the interquartile range. The whiskers cover the 95% confidence interval.

Table A.3
Cumulative Survival Probability (CSP) fitting parameters in 2021.

	Weibull		Import-Gaussian			R^2 values		Optimum distribution
Country	γ	β	δ	μ	σ	R_W^2	R_W^2G	distribution
AUT	16,7	2,9	–	–	–	0,99	0,99	Weibull
BEL	11,9	2,0	–	–	–	0,99	0,99	Weibull
BGR	40,0	6,0	100,0	20,9	6,2	–	0,81	WG
CHE	16,2	3,1	–	–	–	0,97	0,96	Weibull
CYP	28,0	6,0	17,1	9,7	5,0	0,39	0,79	WG
CZE	30,3	6,0	13,7	18,7	5,6	0,44	0,77	WG
DEU	15,7	2,3	–	–	–	0,99	0,99	Weibull
DNK	16,6	3,0	–	–	–	0,98	0,98	Weibull
ESP	21,2	3,3	–	–	–	0,98	0,98	Weibull
EST	37,6	6,0	17,5	21,1	6,1	0,16	0,73	WG
FIN	21,7	4,8	–	–	–	0,97	0,98	Weibull
FRA	18,9	3,3	–	–	–	0,90	0,92	Weibull
GRC	37,1	6,0	–	–	–	0,41	0,43	Weibull
HRV	28,9	6,0	16,5	12,3	8,7	0,51	0,81	WG
HUN	26,1	6,0	10,4	12,6	5,0	0,62	0,90	WG
IRL	16,0	6,0	7,0	5,0	5,0	0,82	0,96	WG
ISL	18,6	5,1	–	–	–	0,99	0,99	Weibull
ITA	21,6	2,8	–	–	–	0,93	0,93	Weibull
LIE	14,9	3,8	–	–	–	0,98	0,99	Weibull
LTU	33,1	6,0	74,9	17,0	5,0	–	0,86	WG
LUX	8,3	2,0	–	–	–	0,95	0,96	Weibull
LVA	33,4	6,0	45,5	18,8	5,0	–	0,82	WG
MLT	33,2	6,0	22,8	12,2	6,6	0,21	0,89	WG
NLD	18,6	5,1	–	–	–	0,98	0,99	Weibull
NOR	19,9	6,0	–	–	–	0,98	0,99	Weibull
POL	32,3	6,0	38,0	17,2	5,0	0,03	0,95	WG
PRT	26,4	6,0	3,3	9,0	5,0	0,92	0,98	WG
ROU	30,8	6,0	39,8	16,7	6,5	0,04	0,64	WG
SVK	28,1	6,0	9,9	16,3	5,0	0,64	0,95	WG
SVN	20,5	6,0	–	–	–	0,95	0,94	Weibull
SWE	18,7	2,7	–	–	–	0,94	0,93	Weibull
UK	15,2	3,8	–	–	–	0,99	0,99	Weibull

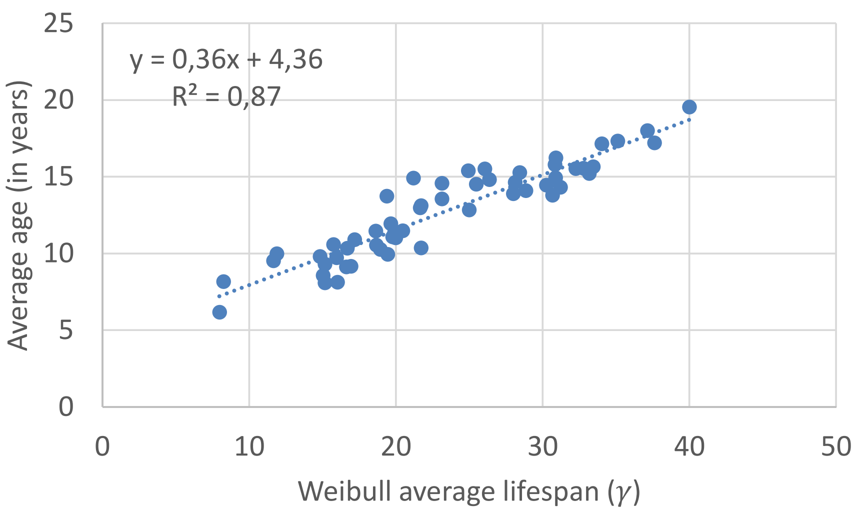

Fig. A.4. Correlation between Weibull average lifespan (γ) and average age of the stock fleet. Data are for the 32 countries for which we have data in 2016 and 2021. In 2016, data for Bulgaria is not available.

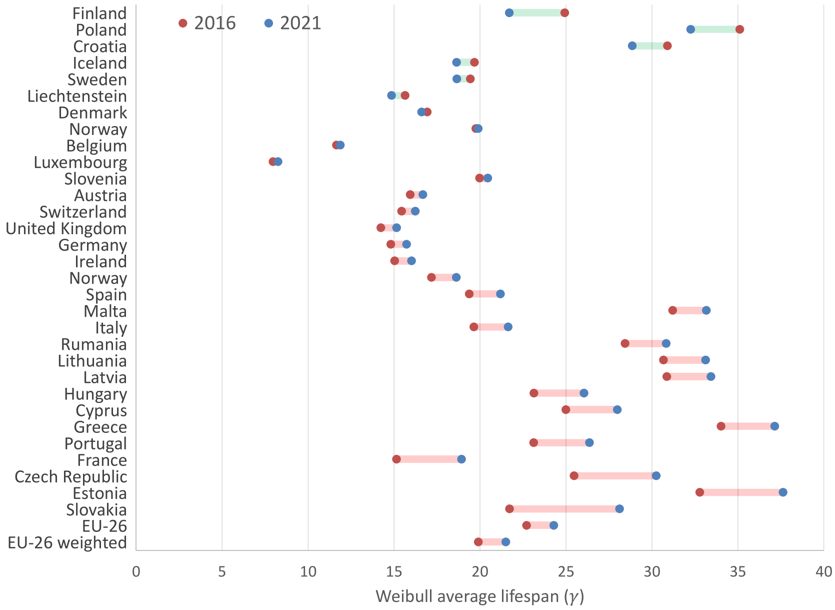

Fig. A.5. Weibull average lifespan (γ) temporal variation. Average lifespan in 2016, and 2021 for 32 European countries. EU-26 average (EU-26) and the weighted average (EU-26 weighted) are included. Red color indicates an increase in the average lifespan from 2016 to 2021. Green indicates a reduction in the average lifespan from 2016 to 2021. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

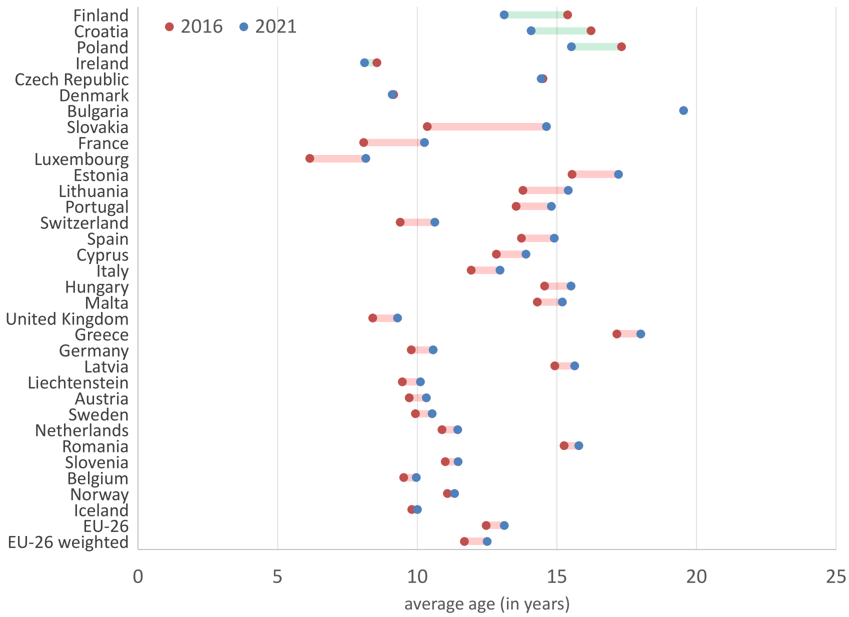

Fig. A.6. Average age temporal variation. Average age in 2016, and 2021 for 32 European countries. EU-26 average (EU-26) and the weighted average (EU-26 weighted) are included. Red color indicates an increase in the average age from 2016 to 2021. Green indicates a reduction in the average age from 2016 to 2021. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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