

## RESEARCH ARTICLE

# Simulation-based analysis of country-specific mitigation strategies to decarbonize the passenger car fleet

A comparison between Germany, Poland, and Norway

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## Abstract

This paper investigates and compares transformation pathways to decarbonize the passenger car fleets of Germany, Poland, and Norway, considering the unique market characteristics of these countries. We develop a dynamic stock and flow model to simulate the evolution of the passenger car fleet in conjunction with the energy sector at a country level and calculate tailpipe and life cycle-oriented greenhouse gas emissions. Using Monte Carlo simulation, we analyze country-specific levers to meet tailpipe emissions targets and their impact on life cycle emissions and the energy system. The results reveal that meeting the European tailpipe emission targets is challenging for Germany and Poland, and much easier for Norway. The main drivers are the level and speed of deployment of electric vehicles and renewable electricity, as well as the rate of the fleet renewal. For countries with a high share of conventional vehicles, synthetic fuels could be promising, but with a significant impact on the energy system. Moreover, an exclusive focus on tailpipe emissions does not imply low life cycle emissions and could even lead to burden shifting. Hence, our results further support the idea that mitigation measures need to be orchestrated and harmonized with country-specific characteristics in order to reduce tailpipe and life cycle emissions as much as possible.

## KEYWORDS

alternative powertrains, climate policy, electric mobility, fleet emissions, industrial ecology, transformation

## 1 | INTRODUCTION

With the European Climate Law, the European Union (EU) pursues ambitious greenhouse gas (GHG) reduction targets for the European economy and society. Compared to 1990 levels, GHG emissions should be reduced by 55% by 2030. As of 2050, the EU strives for net-zero GHG emissions (Regulation (EU) 2021/1119).

One important driver of the GHG emissions is the passenger car sector. With around 440 million tons of CO<sub>2</sub> equivalents (CO<sub>2</sub>e) emitted in the EU in 2021, the combustion of fossil fuels in passenger cars contributed to almost 60% of the total road transport emissions. In turn, road transport

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accounted for more than 20% of the overall GHG emissions in the EU. It is also the only major economic sector in the EU that is not on track to reduce emissions at least to 1990 levels (EEA, 2022b, 2023; Eurostat, 2023a).

While new mobility concepts such as multimodal travel or car sharing have been discussed for more than a decade as promising strategies to decarbonize passenger transport (EEA, 2022a; Maier et al., 2023), the number of passenger cars in the EU is still growing (Eurostat, 2024). This might be especially due to the freedom of mobility and the status provided by private passenger cars (Moody et al., 2021), as well as the importance of the automotive industry for the economy (Mattioli et al., 2020). It is therefore not surprising that much of the debate on how to reduce GHG emissions from passenger cars centers on technological solutions to reduce tailpipe emissions. Some of the most prominent measures are the accelerated market penetration of electric vehicles (EVs) (including battery electric vehicles [BEVs], plug-in hybrid electric vehicles [PHEVs], and fuel-cell electric vehicles [FCEVs]), the use of alternative fuels (e.g., synthetic fuels [e-fuels]), and the ban of vehicles with internal combustion engine (ICEVs).

The discussion about the selection of effective measures to comply with the EU GHG reduction targets is controversial. Often, the focus is on fleet emissions of newly registered passenger cars, and less priority is given to existing car fleets on the road. When considering the entire vehicle stock, the assessment of abatement measures becomes more challenging due to complex market dynamics, such as the inertia to replace old ICEVs with new EVs. In addition, interdependencies between the transport sector and other economic activities (e.g., vehicle and battery production, fuel production, and electricity generation) exist, which call for an integrated fleet and life cycle orientation to avoid burden shifting and unintended side effects (Field et al., 2000; Garcia & Freire, 2017).

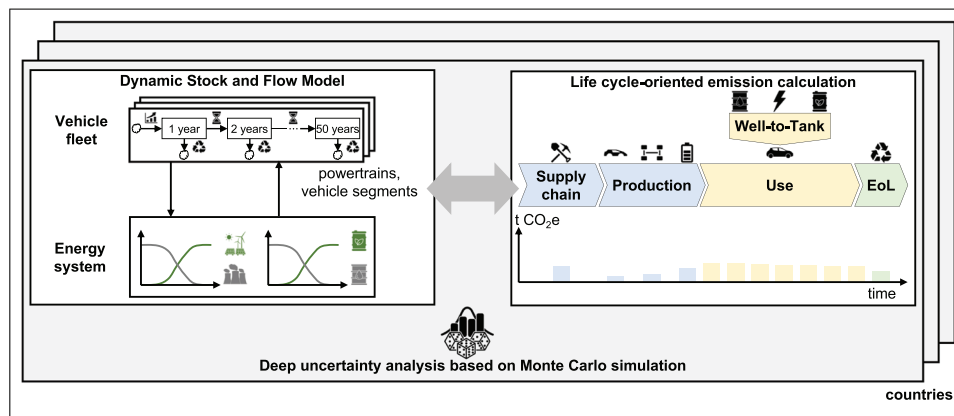
Because of this complexity, it is highly unlikely that a “silver bullet,” that is, one single measure, will solve all problems. Also, a “one-strategy-fits-all” approach may be problematic since individual countries have different characteristics and prerequisites, particularly in terms of vehicle sales (e.g., EV share), composition of the existing vehicle fleet (e.g., size, age distribution, powertrain mix, and fuel consumption), driving behavior of car owners (e.g., annual mileage), and energy mix (e.g., share of renewable energies). For example, a country with low EV penetration and slow vehicle turnover might rely more on e-fuels and ICEV bans than one with a high share of newer EVs.

The assessment of decarbonization pathways for the European car fleet has received considerable attention in the scientific community. However, only two studies consider at least the EU's 2030 emission reduction target with an integrated fleet and life cycle perspective. Tang et al. (2023) assess the GHG emissions of the European passenger car fleet from 2021 to 2040, considering production emissions, well-to-tank (WtT) emissions (only for BEVs), and tank-to-wheel (TtW) emissions. The GHG mitigation measures emphasize BEV market penetration and an accelerated ICEV phase-out, leading to three study scenarios. Dirnhaichner et al. (2022) analyze the life cycle impacts of decarbonization pathways for the European light-duty vehicles (LDV) fleet between 2020 and 2050. They calculate fleet emissions over the LDV life cycle for six mitigation scenarios, which vary by powertrain technology (ICEV, BEV, and FCEV), synthetic fuel availability, and individual mobility demand. Both studies partially address prevailing uncertainties through local sensitivity analyses of individual parameters.

The studies offer initial insights into decarbonization pathways for European car fleets. However, none of the scenarios studied achieves a 55% GHG reduction from 1990 levels, even with ambitious assumptions for EV demand, e-fuel availability, and ICEV phase-out. Moreover, a rapid and widespread EV deployment could shift GHG emissions to vehicle production, requiring a simultaneous renewable electricity ramp-up of e-fuels would further increase electricity demand, emphasizing the need to reduce car use. These findings align with Gómez Vilchez and Jochem (2020), Rottoli et al. (2021), and Zhang et al. (2023).

Despite extensive research on decarbonizing the European passenger car fleet, three major limitations are evident. First, a thorough analysis of mitigation measures for individual countries is largely lacking. Country-specific input parameters are somewhat considered, but their influence on the results is rarely discussed. Neglecting these nuances hinders the development of tailored and effective national mitigation strategies. Second, the studied mitigation scenarios typically focus on individual measures instead of exploring combinations, limiting the understanding of synergies and trade-offs along with their implications for GHG reduction targets. Third, the studies often inadequately address the underlying uncertainties of the evolving GHG fleet emissions until 2050, ranging from technological advances to market dynamics. By focusing primarily on deterministic scenarios, they lack an exploratory approach that examines the complex interplay of multiple uncertain factors and their impact on decarbonization pathways (Bankes, 1993; Maier et al., 2016).

We investigate how the effectiveness of country-specific mitigation strategies to decarbonize passenger car fleets can be improved by considering (1) the unique market characteristics, (2) the synergies and trade-offs between abatement measures, (3) the interdependencies between tailpipe and life cycle emissions, and (4) the high uncertainty in the passenger car market's evolution. This study offers a substantial contribution to the academic discourse on the decarbonization of passenger car fleets. By elucidating key levers and barriers in the development of tailored mitigation strategies, it aims to support both industrial-managers and policy-makers in their decision-making processes. The analysis employs a dynamic stock and flow model to simulate the evolution of passenger car fleets alongside the energy sector at country level. The model calculates life cycle-oriented GHG emissions, and we use Monte Carlo simulation to conduct an exploratory analysis under deep uncertainty with respect to various mitigation measures (EV market penetration, e-fuel ramp-up, and ICEV bans) and market conditions (e.g., mileage, motorization rate and renewable electricity share). We analyze Germany, Poland, and Norway, which are countries with significant differences in passenger car sales, fleets, and energy systems, to identify conditions and transition pathways under which compliance with tailpipe emission targets and the successful transition to net-zero GHG emissions are achievable, and which transformation pathways least affect the energy system. From this, we identify general and



**FIGURE 1** Overview of the simulation model, which integrates system dynamics modeling, life cycle assessment, and Monte Carlo simulation.

country-specific mitigation strategies and necessary conditions to support the decarbonization of the passenger car fleet from both a tailpipe and a life cycle perspective.

The remainder of this paper is organized as follows: In Section 2, we present our simulation approach for analyzing transformation pathways of the passenger car fleet toward zero emissions and summarize the underlying assumptions and related data. In Section 3, we present our numerical results and derive the main levers for decarbonizing passenger car fleets at the country level. We conclude with a discussion of our main findings and avenues for future research.

## 2 | METHODS

### 2.1 | Simulation-based analysis of transformation pathways

This study aims to analyze and compare both tailpipe and life cycle emissions across a large set of transformation pathways for passenger car fleets in Germany, Poland, and Norway from 2023 to 2050. We propose a simulation-based approach (Figure 1) comprising a dynamic stock and flow model that captures the interdependent developments of the vehicle fleet and energy system (Section 2.2), a life cycle-oriented emission calculation model (Section 2.3), and a deep uncertainty analysis using Monte Carlo simulation (Section 2.4). Deep uncertainty refers to the challenges of informed decision-making in contexts with multiple plausible futures (Maier et al., 2016). According to Lempert et al. (2003) and Walker et al. (2013), it arises when decision-makers are unclear about system interactions, probability distributions of key parameters, and evaluating alternative outcomes. Kwakkel et al. (2010) state that deep uncertainty includes situations where various potential futures exist but cannot be effectively ranked by likelihood. Hence, “deep uncertainty analysis” denotes a systematic approach to explore these complexities, enabling the evaluation of diverse outcomes and strategies for more robust insights given the unpredictability of the automotive market. A detailed description of the simulation model and data is available in Supporting Information S1.

### 2.2 | Key features of the dynamic stock and flow model

The dynamic stock and flow model depicts the vehicle fleet composition and energy system characteristics in each country. To quantify the demand for passenger vehicles, country-specific vehicle markets are modeled using data from the respective countries. Vehicles are categorized by powertrain type (ICEV, PHEV, and BEV) and segment (mini, small, medium, large, executive, luxury, sport, SUV, large SUV, and minivan). Each vehicle type has a sequence of stocks representing the number of vehicles in specific age cohorts (aging chain). As the simulation progresses, new vehicles enter the first cohort, while existing vehicles progress to the next or exit the aging chain upon reaching end-of-life, as determined by country-specific survival probabilities (Held et al., 2021). By considering powertrain, segment, age, and country, specific vehicle parameters such as fuel/electricity consumption, annual mileage, and production emissions can be defined.

The market diffusion of BEVs and PHEVs is modeled using the Gompertz function, which is well-suited for the analysis of asymmetric growth pattern with slow initial adoption and gradual adaptation. The Gompertz function smooths the transition to market saturation and often aligns more closely with real-world technology adoption curves than other functions, making it suitable for studying powertrain diffusion (Kumar et al., 2022). Although policy-sensitive approaches like random utility theory (e.g., multinomial logit models) could provide insights into consumer choice and responses to policy interventions (Thies et al., 2016), we chose the Gompertz function for its ability to incorporate uncertainties while keeping

the modeling process practical by limiting the number of required simulations. It is defined by the three parameters  $a$ ,  $b$ , and  $c$ .

$$f(t) = a \cdot e^{-b \cdot e^{-c \cdot (t-t_0)}} \quad (1)$$

The potentially achievable market share of EVs corresponds to parameter  $a$ , which is varied within a specific range for each country in the Monte Carlo simulation. Parameter  $b$  is tailored to match the current EV market conditions in each country at the beginning of the simulation. Parameter  $c$  controls the shape of the Gompertz function, reflecting the speed of market penetration. Initially based on each country's current EV market share growth rate,  $c$  can be adjusted within a defined range to reflect potential changes in penetration speed. As BEV and PHEV sales expand, ICEVs lose market share. PHEVs may further lose market share to BEVs. Should ICEVs and PHEVs be banned, BEVs would capture 100% of the market.

The Gompertz function is also employed to model the expansion of renewable energy sources in each country (Cherp et al., 2021), with uncertain parameters adjusted in the Monte Carlo simulation. As renewable energy expands, nuclear and fossil energy sources diminish in these countries. The time-variant energy mix is used for the dynamic calculation of GHG emissions.

### 2.3 | Approach for the calculation of tailpipe and life cycle-oriented fleet emissions

Our study's system boundaries encompass a cradle-to-grave perspective, from vehicle production to use (including fuel and electricity provision) and end-of-life.

Production emissions are compiled for the glider (vehicle body), the powertrain, and battery components, differentiated by vehicle type based on mass, power, or battery size. Due to varying import shares of new vehicles, production emissions are calculated specifically for each country. Emission are split into a fixed component for the upstream supply chain and a variable component derived from the cumulative energy demand (CED) for production and the average energy mix at the production location, both within (OICA, 2023) and outside (ACEA, 2023) Europe.

During the vehicle use phase, both direct emissions from vehicle operation (TtW) and indirect emissions from energy carrier (fuel, e-fuel, and electricity) production (WtT) are considered. These emissions depend on vehicle-specific fuel and electricity consumption. TtW emissions, or tailpipe emissions, are determined by the fuel consumption of ICEVs and PHEVs, with 1L of fuel combustion (average of petrol and diesel) resulting in 2.49 kg CO<sub>2</sub>e emissions (Prussi et al., 2020). In contrast, electric vehicles have zero tailpipe emissions (Orecchini & Santiangeli, 2010). WtT emissions vary by energy carrier and the dynamic share of renewables in the energy system. Besides fossil fuel, ICEVs/PHEVs can be operated with e-fuels (synthesized from hydrogen and captured CO<sub>2</sub>) (Ueckerdt et al., 2021). Assuming hydrogen production and direct air capture based on renewable energies, e-fuel are almost carbon neutral from a life cycle perspective as they release the previously captured amount of CO<sub>2</sub> when combusted. BEVs and PHEVs are assumed to be recharged with the current electricity mix. The PHEV driving mode (fuel or electric) is influenced by the battery capacity, modeled by a utility factor (Plötz et al., 2020). A higher battery capacity increases the proportion of electric driving. Additional maintenance-related emissions may occur for all vehicle types.

At each vehicle's end-of-life, a fixed, vehicle-specific emission amount is considered for recycling.

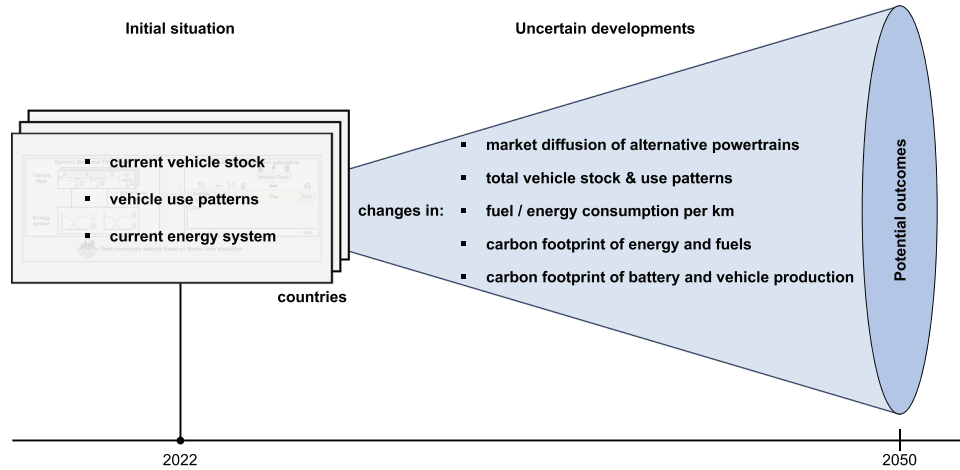
During the simulation, life cycle emissions are calculated for each vehicle and aggregated to determine the total life cycle-oriented fleet emissions.

Our analysis avoids double counting by focusing initially on tailpipe emissions and their reduction targets while also providing a comprehensive assessment of life cycle emissions. This enables the analysis of additional emissions in other sectors due to burden shifting during the fleet transition. Although burden shifting is well recognized, life cycle GHG emissions are often overlooked in transport decarbonization efforts under the "polluter pays principle" (Bleeker, 2009; European Court of Auditors, 2021). This oversight is significant for aligning with EU environmental policy (Official Journal of the European Union, 2016). Our methodology adheres to the producer responsibility principle, capturing all emissions associated with the product. Without this approach, vehicle production might shift to other countries, leading to arbitrary emission budgets. Consequently, automakers bear indirect responsibility for the entire supply chain, a consideration increasingly recognized in current legislation, especially regarding electric vehicle batteries.

### 2.4 | Consideration of uncertainties using Monte Carlo simulation

Many of the parameters that define a transformation pathway are uncertain. To address this, we pursue an open exploration approach based on Monte Carlo simulation. Each simulation run represents a possible transformation pathway. We aim to identify the most successful pathways with lowest total CO<sub>2</sub>e emissions over the simulation period. This involves a four-step procedure.

- (i) Specify plausible value ranges for each uncertain parameter (Section 2.5), considering country-specific characteristics. In total, we identify 72 uncertain parameters.



**FIGURE 2** Overview of initial parameters and uncertain developments in the simulation model.

(ii) Before starting the simulation, initialize each parameter with a random value drawn from the plausible range. Execute the simulation model with these parameters and compute the resulting performance indicators. For a global sensitivity analysis based on the total sensitivity index,

$$N = n \cdot (2 \cdot U + 2) \quad (2)$$

model evaluations are needed (Saltelli et al., 2010), where  $U$  represents the number of uncertain input parameters and  $n$  is a proportionality factor determined by the application. The value of  $n$  ranges from 100 to 10,000, with  $n$  being the result of  $2^x$  (Pianosi & Wagener, 2015). For this study, we set  $n = 4096$ , resulting in 598,016 model evaluations, which we refer to as simulation runs.

- (iii) After completing all simulation runs, analyze the performance indicators to identify successful transformation pathways for each country. We initially focus on tailpipe emissions, considering legal requirements and thresholds. Subsequently, we compare these with the corresponding life cycle emissions to determine if effective tailpipe emission pathways also yield favorable life cycle emissions.
- (iv) Investigate the characteristics of different transformation pathways. We apply variance-based global sensitivity analysis (Sobol' indices, based on Sobol', 2001) and feature scoring (Geurts et al., 2006) to identify parameters with a strong influence on transformation success. Next, we compare these influential parameters across countries and analyze how the different pathways affect the energy system, in terms of e-fuel and renewable energy demand.

## 2.5 | Initialization and execution of the model for specific countries

The analysis is conducted at country level, focusing on three representative European countries with distinct characteristics. First, we examine Norway, a leader in BEV registrations, with a 79.3% share of BEV sales in 2022. Due to early and rapid BEV adoption, over 20% of vehicles in Norway are already electric (European Commission, 2024b). Second, we explore Germany, which had a 17.5% BEV registration share in 2022 (European Commission, 2024b) and possesses the largest passenger car market in Europe with 48.761 million vehicles on the road (Eurostat, 2024). Third, we investigate Poland, a laggard in BEV diffusion, with a BEV sales share of 2.7% in 2022 (European Commission, 2024b) and a rather old vehicle fleet due to longer vehicle lifetimes.

Figure 2 outlines the parameters used for model initialization and the uncertain parameters varied during model execution. The simulation model is initialized with country-specific values from 2022, reflecting the vehicle stock composition by segment and age, vehicle use patterns like lifetime and annual mileage, and the energy mix in terms of renewable, nuclear, and fossil electricity.

In the Monte Carlo simulation, the EV market development (in terms of market potential and diffusion speed) is the major driver of uncertainty. We also examine changes in total vehicle stock based on country-specific mobility demands and motorization rates. The carbon footprint of battery and vehicle production may evolve during the simulation, as will the development of the renewable energy (maximum potential and deployment speed).

Table 1 presents a detailed overview of the country-specific parameters. All values refer to the target year 2050 and are extrapolated linearly from 2023 to 2050, except for powertrain diffusion and renewable electricity share, which are modeled using a Gompertz curve.

**TABLE 1** Country-specific market parameters for the initialization of the simulation model and for the description of potential developments.

Parameter	Unit	Germany	Norway	Poland	Reference
<i>Initial situation (2022)</i>					
Population	million people	83.237	5.425	37.654	(Eurostat, 2023b)
Vehicle stock	million vehicles	48.761	3.019	21.458	(Eurostat, 2024)
Motorization rate	vehicles per 1,000 people	585	553	572	(Eurostat, 2024a)
Composition of vehicle stock	%	96.15	73.09	99.84	(European Commission, 2024b)
- ICEV		1.77	6.78	0.02	
- PHEV		2.08	20.13	0.14	
- BEV					
Sales shares	%	68.9	11.4	94.7	(European Commission, 2024b)
- ICEV		13.6	9.3	2.6	
- PHEV		17.5	79.3	2.7	
- BEV					
Annual mileage per vehicle	km per year	12,545	11,097	7,857	(Eurostat, 2023d; Statistics Norway, 2023; Statistics Poland, 2023)
Share of renewable electricity	%	43.5	99.0	21.2	(Ritchie et al., 2024)
<i>Potential development (situation in 2050 compared to initial situation)</i>					
Population	million people	74.4 to 88.9	5.3 to 6.5	33.1 to 35.5	(Eurostat, 2023c)
Future motorization rate	%	-10 to +10			Own assumption
Mobility demand (annual vehicle-kilometers traveled per 1,1000 people)	%	-10 to +10			Own assumption
Potential sales share BEV	%	17.5 to 100	79.3 to 100	2.7 to 100	(European Commission, 2024b) Upper bound own assumption
Acceleration of BEV market penetration	%	-25 to +25			Own assumption
Future share renewable electricity	%	43.5 to 100	99.0 to 100	21.2 to 100	(Ritchie et al., 2024) Upper bound own assumption
Acceleration of RE ramp-up	%	-25 to +25			Own assumption
ICEV/PHEV ban		2035 or no ban			Own assumption
Vehicle lifespan of different powertrains	%	-25 to +25			Own assumption
E-fuel share in 2050	%	0 to 100			Own assumption
Reduction of CED for vehicle production:	%				
- Glider		-40 to 0			(Wang et al., 2021)
- Powertrain		-10 to 0			(Sacchi et al., 2022; Wang et al., 2021)
- Battery		-60 to 0			(Chordia et al., 2021; Dai et al., 2019; Davidsson Kurland, 2020; Degen & Schütte, 2022; Hung et al., 2021; Schmidt et al., 2019; Sun et al., 2020; Wang et al., 2021; Winjobi et al., 2022)

(Continues)

**TABLE 1** (Continued)

Parameter	Unit	Germany	Norway	Poland	Reference
- Assembly		-60 to 0			(Benitez et al., 2021; Wang et al., 2021)
Reduction of fixed production emissions:	%				
- Glider		-10 to 0			(Buberger et al., 2022; Ellingsen et al., 2016; European Commission et al., 2020; Hung et al., 2021)
- Battery		-50 to 0			(Hung et al., 2021; Winjobi et al., 2022)
Reduction thermal energy usage during production	%	-100 to 0			(Chordia et al., 2021; Dai et al., 2019; Degen & Schütte, 2022; Hung et al., 2021; Sun et al., 2020; Winjobi et al., 2022)

### 3 | RESULTS

In this chapter, we first examine the tailpipe emissions (Section 3.1) before expanding the focus to life cycle emissions (Section 3.2). Finally, we analyze the implications for the energy system, particularly regarding the ramp-up of e-fuel production capacity and renewable energy (Section 3.3).

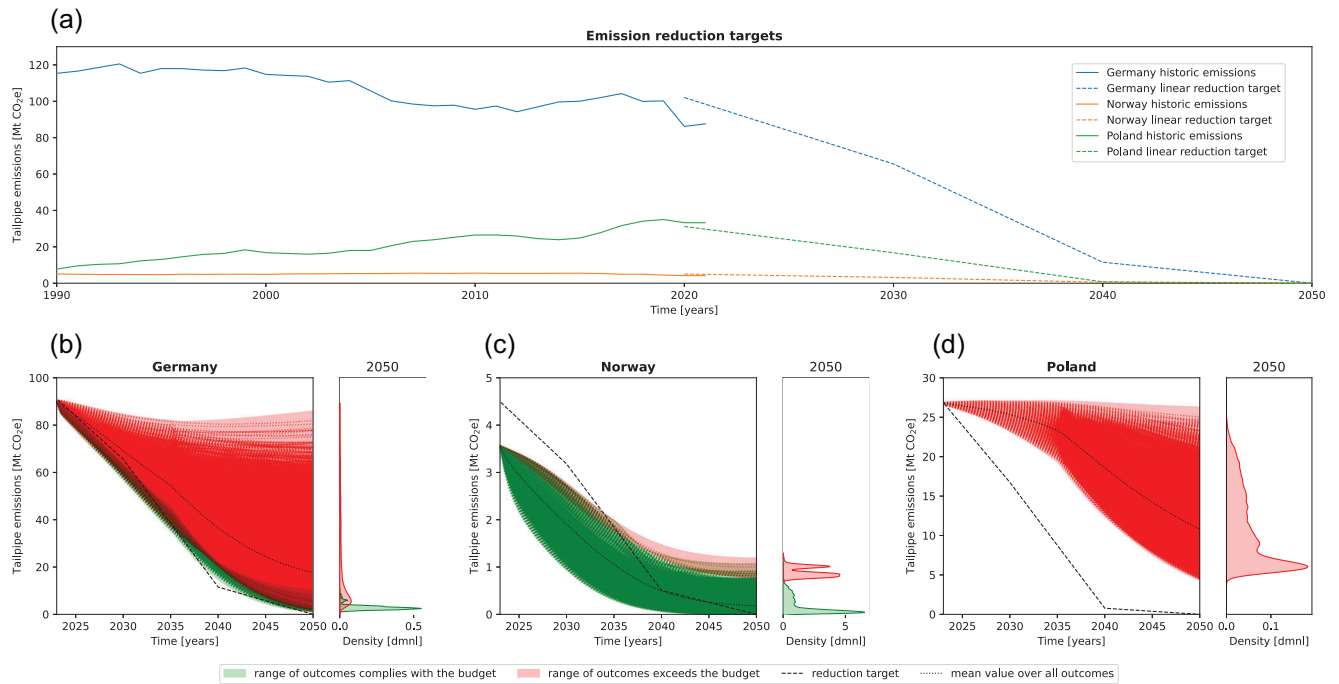
#### 3.1 | Analysis of tailpipe emissions

Figure 3a displays the linear reduction targets for tailpipe emissions in Germany, Norway, and Poland. The 2030 reduction targets are based on Regulation (EU) 2018/842 and the Ministry of Climate and Environment (2021). For 2040, we apply the EU's recommended target of a 90% reduction from 2005 levels, and for 2050, the aim is to achieve GHG neutrality in alignment with the European Climate Law (European Commission, 2024a). From these reduction targets, we derive a GHG tailpipe emission budget for each country from 2023 to 2050 (area under the linear reduction curve). Figure 3b–d illustrates potential tailpipe emission pathways, their budget compliance, and the probability density estimation of 2050 tailpipe emissions.

A wide range of GHG tailpipe emission pathways until 2050 is possible, particularly for Germany and Poland. In Germany, successful and unsuccessful pathways may overlap in some periods. Therefore, successful pathways might not always remain below the linear reduction target but could catch up later. Strict adherence to the linear targets is infeasible for both Germany and Poland. The mean values of all simulation runs (dotted lines) suggest that Norway will likely remain below the linear target, whereas Germany and Poland will not. Germany complies with the derived emission budget in 2.66% of all runs, and Norway in 99.97%, whereas Poland never complies. Although tailpipe emissions generally decline in all countries toward 2050, achieving zero emissions is not expected within this time. In 2050, Germany's remaining emissions are estimated at  $17.59 \pm 16.27$  Mt CO<sub>2</sub>e (mean  $\pm$  standard deviation), Norway at  $0.18 \pm 0.09$  Mt CO<sub>2</sub>e, and Poland at  $10.80 \pm 9.49$  Mt CO<sub>2</sub>e. In Germany, non-complying pathways exhibit a broad spectrum of emission values for 2050, clustering predominantly in the lower range but still exceeding the budget cumulatively. Budget-compliant scenarios are correlated with very low emissions in 2050. In contrast, Norway shows a strong correlation between budget compliance and low emissions in 2050, as non-compliance tends to result in higher emissions, reflected by minimal overlap of the density functions. Poland shows a high likelihood of significant emissions in 2050, with the broad density curve indicating high variability in emissions that year.

#### 3.2 | Analysis of life cycle emissions

Figure 4 compares the cumulative tailpipe and life cycle emissions for each country across 598,016 simulation runs, illustrating that similar levels of tailpipe emissions can lead to varying cumulative life cycle fleet emissions. While this holds true for all countries, differences regarding the four quadrants, which separate runs by the level of cumulative emissions achieved (tailpipe vs. life cycle), can be observed. The causes for this country-specific behavior are identified through global sensitivity analysis and feature scoring (detailed in Supporting Information S1) to derive the parameters that significantly affect tailpipe and/or life cycle emissions. These parameters will be highlighted in the following explanations of the results.



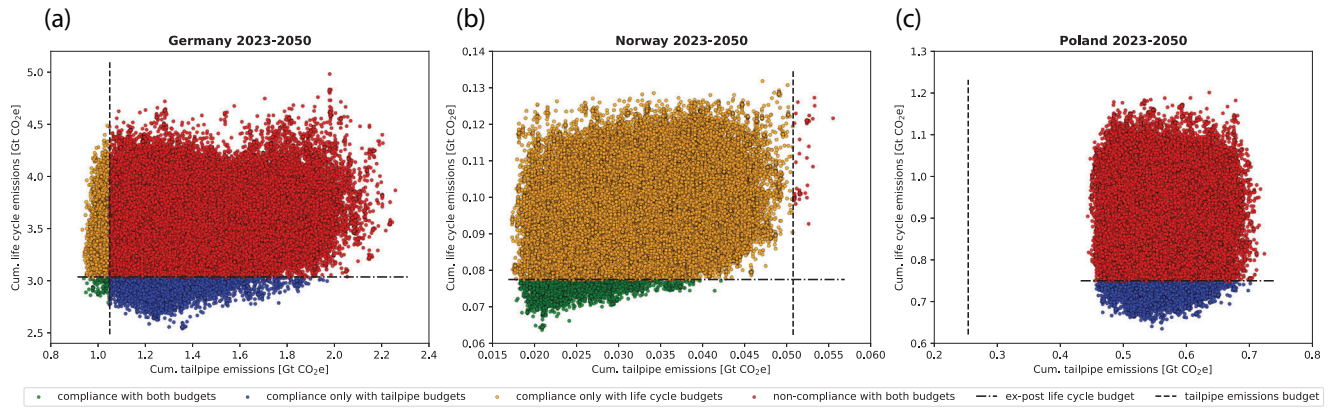
**FIGURE 3** Overview of the development of tailpipe emissions from vehicles in Germany, Norway, and Poland. The top graph shows the historical tailpipe emissions since 1990 alongside the linear reduction targets for each country until 2050 (a). The graphs below display the projected tailpipe emissions from 2023 to 2050 for Germany (b), Norway (c), and Poland (d), based on 598,016 simulation runs. Green curves indicate that cumulative tailpipe emissions remain below the derived GHG budget, while the red curves indicate budget exceedance. Each graph includes the European Commission's linear reduction target as a dashed line and the median value across all outcomes as a dotted line. To the right of country's projection, a probability density graph details anticipated tailpipe emissions for 2050. Underlying data are provided in Supporting Information S2.

Only a subset of the model evaluations that are successful in reducing tailpipe emissions also performs well in life cycle emissions, indicated by the green quadrants in Figure 4 (Germany 0.05%, Norway 2.6%, and Poland 0% of all runs). For Germany, these successful runs are driven by a high BEV sales share ( $90.63 \pm 6.47\%$ ), a decrease in ICEV lifespan ( $-19.37 \pm 3.78\%$ ) facilitating the shift to BEVs, and an ICEV ban in 2035 (77.92% of all cases), along with high shares of renewable energy ( $93.6 \pm 4.49\%$ ) and e-fuels ( $70.83 \pm 24.97\%$ ). A decreasing mobility demand due to shrinking population ( $77,302,477 \pm 2,692,532$ ) is also beneficial. For Norway, reduced ICEV lifetimes ( $-15.09 \pm 8.27\%$ ) and high BEV sales ( $93.66 \pm 4.85\%$ ) are crucial, with the already substantial BEV presence further supported by extended BEV lifetimes ( $18.47 \pm 5.25\%$ ).

Some outcomes with successful tailpipe emission reductions may underperform from a life cycle perspective (Figure 4, top left quadrant, orange; Germany 2.61%, Norway 97.35%, and Poland 0%). For Germany, these developments involve high BEV sales ( $87.09 \pm 10.10\%$ ), reduced ICEV lifespan ( $-20.60 \pm 3.68\%$ ), and ICEV bans (91.98%), combined with slightly lower shares of renewable energy ( $69.88 \pm 16.01\%$ ) and e-fuels ( $48.77 \pm 28.6\%$ ) and slightly increased mobility demand due to higher population ( $80,267,932 \pm 3,815,956$ ) compared to the green quadrant. Norway's results in this quadrant show a minor increase in ICEV lifetime ( $0.4 \pm 14.34\%$ ) and a high BEV sales share ( $89.56 \pm 5.96\%$ ), but a decline in BEV lifetime ( $-0.50 \pm 14.27\%$ ).

The blue lower right quadrant in Figure 4 includes runs that exceed the tailpipe threshold but perform relatively well from a life cycle perspective (Germany 5%, Norway 0%, and Poland 4.82%). For Germany, these involve lower BEV sales shares ( $68.70 \pm 21.15\%$ ), longer ICEV lifetimes ( $8.92 \pm 11.94\%$ ), fewer ICEV bans (56.12%), high shares of renewable energy ( $89.67 \pm 8.26\%$ ) and e-fuels ( $74.53 \pm 20.5\%$ ), and decreasing mobility demand from a shrinking population ( $78,594,950 \pm 3,313,430$ ). This pattern holds for Poland, where, despite sporadic ICEV bans (59.57%) and increased ICEV lifetime ( $10.62 \pm 10.77\%$ ) with low BEV sales potential ( $55.89 \pm 27.27\%$ ), high shares of e-fuels ( $86.74 \pm 10.98\%$ ) and renewable energy ( $86.05 \pm 11.36\%$ ) result in favorable life cycle emissions.

Runs that perform poorly regarding both tailpipe and life cycle emissions are displayed in the red, top right quadrant in Figure 4 (Germany 92.34%, Norway 0.03%, and Poland 95.18%). For Germany, these are characterized by low BEV sales ( $57.40 \pm 23.59\%$ ), fewer ICEV bans (51.53%), extended ICEV lifetimes ( $0.11 \pm 14.18\%$ ), and low shares of renewable energy ( $70.52 \pm 16.24\%$ ) and e-fuels ( $48.70 \pm 28.67\%$ ), alongside a higher mobility demand due to population growth ( $81,883,588 \pm 4,149,609$ ). In the few cases for Norway, increased ICEV lifetimes ( $22.73 \pm 1.99\%$ ), steady BEV sales ( $80.73 \pm 0.65\%$ ), and shorter BEV lifetimes ( $-2.90 \pm 14.53\%$ ) are the main drivers. For Poland, the outcomes exhibit sporadic ICEV bans (50.48%), slightly reduced ICEV lifetimes ( $-0.54 \pm 14.39\%$ ), low BEV sales potential ( $51.11 \pm 28.11\%$ ), and a low share of e-fuels ( $48.14 \pm 28.24\%$ ) and renewable energy ( $59.23 \pm 22.46\%$ ).



**FIGURE 4** Comparison of cumulative tailpipe emissions and cumulative life cycle emissions for Germany (a), Norway (b), and Poland (c) across 598,016 simulation runs. The vertical dashed line indicates the GHG tailpipe emissions budget. Given the absence of an official life cycle GHG emissions budget, we employ country-specific ex post thresholds based on the simulation outcomes. The horizontal dashed line separates simulation runs that exceed the minimum cumulative life cycle GHG emissions by more than 20% of the difference between the maximum and minimum cumulative life cycle GHG emissions versus those that do not exceed this amount. Green indicates runs that comply with both targets, while red indicates non-compliance with both. Blue represents runs that miss the tailpipe GHG emissions budget but achieve the target for cumulative life cycle emissions, and orange signifies those that meet the tailpipe budget but fall short on life cycle emissions. Supporting data is provided in Supporting Information S2.

### 3.3 | Implications for the energy system

The results for Germany and Poland suggest that e-fuels plays an important role in reducing cumulative life cycle emissions (green and blue quadrants). They help in mitigating the emissions from the large ICEV fleets and the delayed transition to BEVs. Figure 5 illustrates notable differences in the maximum e-fuel demand across the countries. Peak demand is projected for Germany in 2034, Norway in 2031, and Poland in 2041, based on the mean outcomes in the green and blue quadrants. These declines after previous peaks results from the increasing BEV share, leading to fewer ICEVs and PHEVs on the road. The peak timing varies due to differences in BEV sales share and vehicle lifespan across countries. Poland's maximum e-fuel demand is 4.22 Gt, which is 58.17% of Germany's 7.26 Gt peak demand, despite having only 44% of Germany's vehicle fleet. This discrepancy arises from Poland's slower vehicle turnover rate, with ICEVs lasting on average 2.37 times longer than in Germany. In summary, e-fuels can reduce emissions from remaining ICEVs but require a substantial increase in renewable electricity.

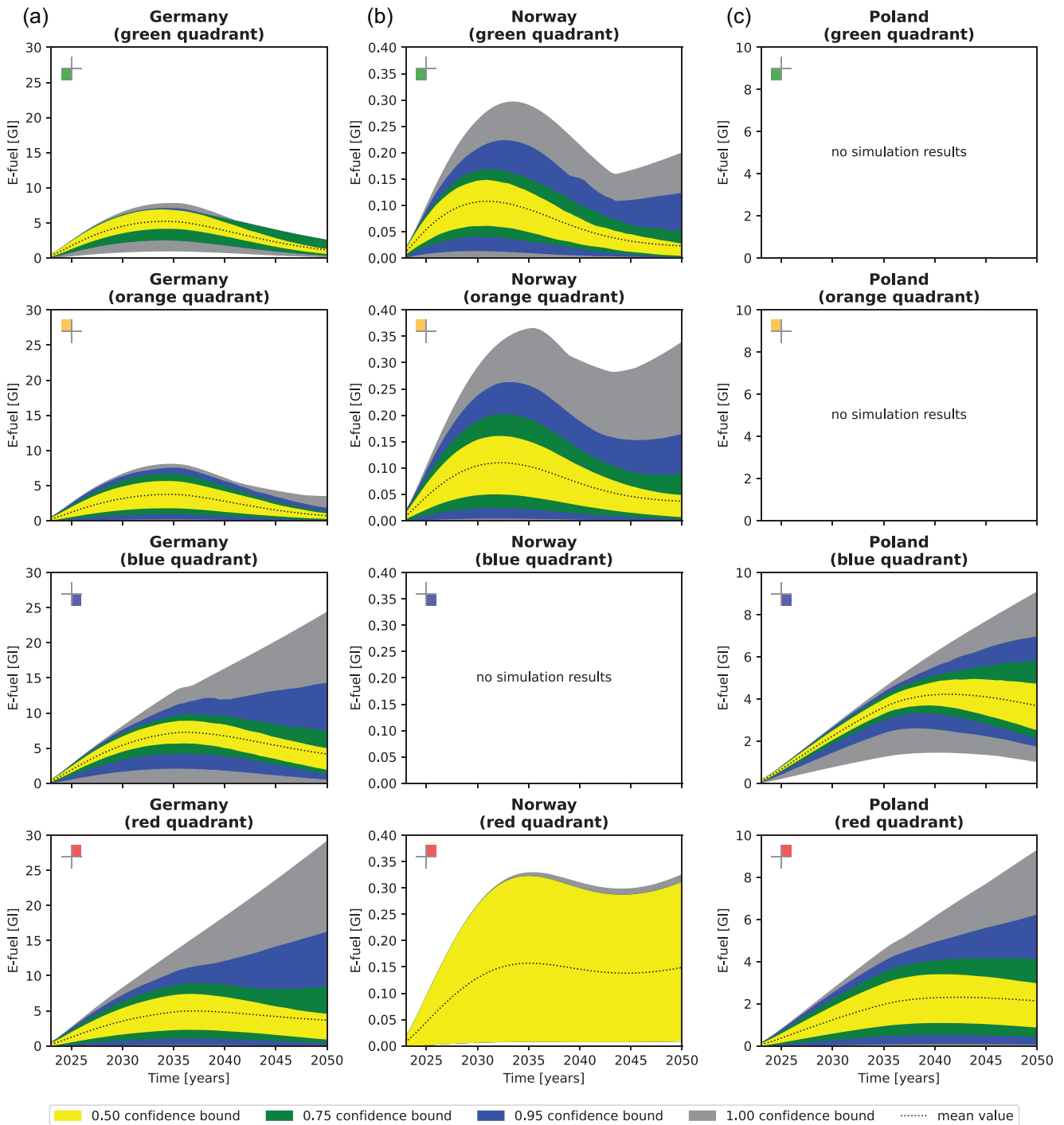
Figure 6 displays the renewable energy demand for passenger cars in Germany, Norway, and Poland. The peak demand for renewable energy is strongly linked to the energy-intensive e-fuel production. Projected maximum renewable energy demands (mean outcomes, green and blue quadrants) are 355.67 TWh in Germany (2037), 11.16 TWh in Norway (2033), and 171.61 TWh in Poland (2043). These values represent 145.93%, 7.38%, and 449.71% of the renewable electricity produced in 2022 in Germany, Norway, and Poland, respectively (Ritchie et al., 2024), indicating a tougher challenge for Germany and Poland.

However, renewable energy demand does not necessarily correlate with cumulative life cycle emissions. As Figure 6 shows, in Germany, desirable outcomes (green and blue quadrants) require 348 to 448 TWh, while undesirable outcomes (orange and red) require 333 to 405 TWh, showing only a 4% to 34% increase for better outcomes. Poland exhibits a similar trend with up to 38% higher renewable energy demand for favorable outcomes due to the limited BEV sales potential and the moderate e-fuels use in the orange and red quadrants. The residual ICEVs require almost the same amount of e-fuels than in the favorable runs, which are characterized by an even higher utilization of e-fuels.

In Norway, average peak demand for renewable energy in the green quadrant is 13.2 TWh, while undesirable outcomes require 14.6 to 20.3 TWh, suggesting even a 10% to 54% lower demand for the desirable outcomes. Norway's already high BEV penetration in early years implies a similar basic level of renewable energy demand for their operation across all runs. Moreover, with fewer ICEVs and consequently less e-fuel production, the peaks in renewable energy demand are less pronounced.

## 4 | DISCUSSION

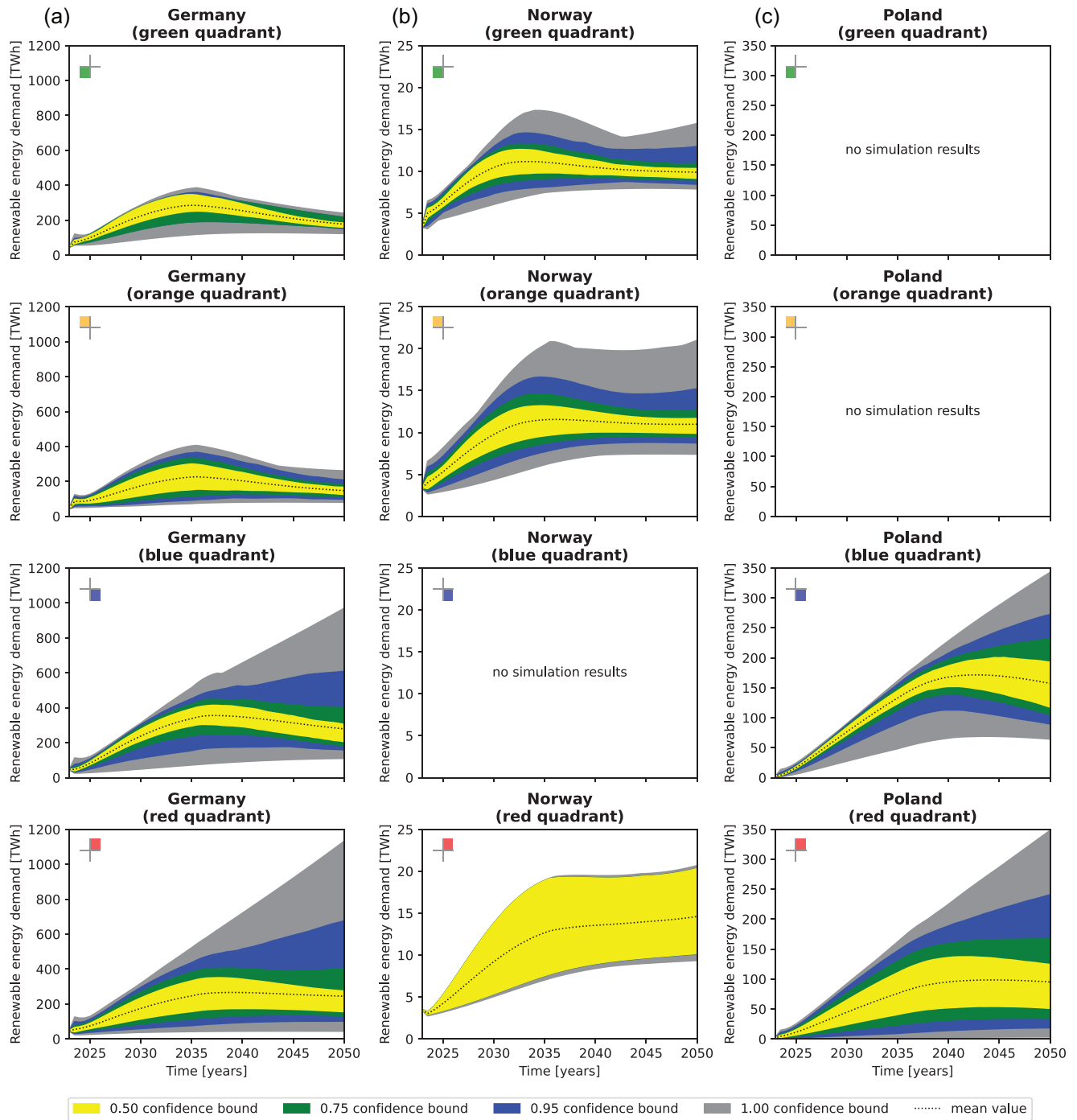
Our study shows that promising strategies for reducing GHG emissions from the passenger cars differ across European countries depending on their progress toward BEV adoption and renewable energy deployment. Even leading and well-advanced countries like Norway and Germany may struggle to meet the existing linear reduction targets for tailpipe fleet emissions. Country-specific emission budgets could provide flexibility, as observed for Norway and to a smaller extent for Germany, but tailpipe emissions may not reach zero by 2050. Hence, countries must compensate for



**FIGURE 5** Projected e-fuel demand in Germany (a), Norway (b), and Poland (c) across 598,016 simulation runs. The mean is represented by the dotted line, while the 0.50, 0.75, 0.95, and 1.00 confidence bounds are depicted in yellow, green, blue, and gray. Underlying data are available in Supporting Information S2.

residual emissions ranging from 0.18 to 17.59 Mt CO<sub>2</sub>e/year through sequestration or other methods. As demonstrated, focusing only on tailpipe emissions can be misleading. Lowering these emissions does not always reduce overall life cycle emissions and may shift the burdens from the use phase to vehicle production.

The variance-based global sensitivity analysis reveals that banning ICEVs can significantly reduce tailpipe emissions, especially in countries with lower market penetration of BEVs. If accompanied by a high BEV market share well before 2035, the reduction can be even more pronounced. However, such a ban might not reduce life cycle emissions without additional measures like e-fuels, especially in Germany and Poland, where ICEV turnover is slower. Mitigating emissions from battery production is also crucial to avoid burden shifting. Moreover, increased motorization rates could undermine overall life cycle emission reductions, even with ICEV bans.



**FIGURE 6** Projection of renewable energy demand for passenger cars in Germany (a), Norway (b), and Poland (c) across 598,016 simulation runs. The mean is represented by the dotted line, while the 0.50, 0.75, 0.95, and 1.00 confidence bounds are depicted in yellow, green, blue, and gray. Underlying data are available in Supporting Information S2.

Effective mitigation measures for both tailpipe and life cycle emissions that also create synergies for greater overall environmental benefits include shortening ICEV lifespans, provided that BEV adoption accelerates. Conversely, extending BEV lifespans helps offsetting the high emissions from battery production, although the delayed recycling may complicate compliance with the targets for the use of secondary battery materials in the new EU Battery Directive (Ginster et al., 2024).

In contrast, some policies beneficial for tailpipe emissions may not reduce life cycle emissions. For example, ICEVs bans are beneficial from a tailpipe perspective, but might have adverse effects on life cycle emissions if BEVs are recharged with a low share of renewable energy. Similarly, trade-offs may arise if BEV production emissions remain high while BEVs are replaced rapidly, preventing the full environmental potential from being realized.

In the case of a slow fleet turnover, e-fuels can be used as an additional measure to decarbonize the existing fleet. As the demand for e-fuels develops with a time lag between different countries, it may be possible to share production capacities. Nevertheless, the role of e-fuels needs to be critically viewed, as production capacities are limited, prices are high, and other industries have no other decarbonization options than hydrogen, which is necessary to produce e-fuels.

Our research adds three major insights to the literature. First, while product-based life cycle assessments identify the greatest GHG reduction potential in battery production and its upstream activities (Biemann et al., 2024), our country-level assessment of car fleets demonstrates that market parameters such as vehicle lifetime, ICEV bans, renewable energy share, and e-fuel utilization have an even stronger impact on cumulative life cycle emissions due to systemic inertia. Second, we demonstrate that the main drivers for emission reduction and their effects on the energy sector vary greatly by country. Third, we illustrate the synergies and trade-offs between several levers that facilitate or impede the decarbonization process. The analysis of these synergies and trade-off is conducted under consideration of multiple uncertain factors, contributing to the development of robust and adaptable strategies for achieving emission targets in Europe's automotive sector.

Several limitations of our study suggest promising areas for future research. First, we use different vehicle segments, but over the simulation time, the share of each vehicle segment remains constant. With the still ongoing trend to bigger cars (IEA, 2024), this might lead to an underestimation of the life cycle GHG emissions of the fleet. Second, we assume that battery supply always meets the demand of BEVs, which might not hold given supply shortages. Moreover, the new European Battery Regulation sets thresholds for the content of recycled battery material in new batteries (EU, 2023). Thus, striving for longer lifetime of BEVs to decrease life cycle emissions may be in conflict with the new regulation, limiting the amount of BEVs that can be produced and sold (Ginster et al., 2024). Third, we neglect the behavior of decision-makers in our model. Since the countries must take additional measures if they exceed GHG emission thresholds, some of the worse simulation runs may be less likely to occur in the future. Fourth, we exclude automated vehicles (Letmathe & Paegert, 2025) and car sharing concepts (Turoń, 2023), which could potentially reduce GHG emissions. However, as reported in the literature, rebound effects from the induced travel demand due to lower generalized travel costs must also be accounted for, since these rebound effects could negate GHG emission reductions and, in extreme cases, lead to higher overall emissions (Morfeldt & Johansson, 2022). Despite these limitations, our comparative framework establishes a solid foundation for future work. It can help refine country-specific transformation pathways and support the development of orchestrated and harmonized mitigation measures that reduce both tailpipe and life cycle emissions.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest. While Christoph Runde and Jörg Wansart were employed by the Volkswagen Group when this study was carried out, the analyses and results were not influenced by the company and do not reflect the views of the Volkswagen Group.

## DATA AVAILABILITY STATEMENT

Data available in article Supporting Information.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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