CALCULATING POTENTIAL EMISSION REDUCTIONS THROUGH THE INTRODUCTION OF ELECTRIC VEHICLES

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ABSTRACT

Electric vehicles are expected to significantly reduce road transport emissions, given an increasingly renewable power generation. While technological issues are more and more being overcome, the economic viability and thus possible adoption is still constrained, mainly by higher prices than for conventional vehicles. However, first vehicles have been available on the market for some time now and many more are expected to arrive soon and at decreasing cost.

In our work we analyze the possible market development for electric vehicles with an application to Germany. We develop a drivetrain choice model with economical, technical and social constraints on the current vehicle registrations and inventory. It estimates the demand for electric vehicles until 2030 for private and commercially registered cars as well as light commercial vehicles.

The results show a replacement potential of more than one fourth of the total German annual mileage for these vehicles. The result has a high granularity to allow for detailed emission calculation along different spatial areas as well as vehicle and engine types. Besides a baseline forecast, our method allows for calculating different scenarios regarding policy actions or the future development of important parameters such as energy prices. The results provide insights for policy measures as well as for transport and environmental modeling.

INTRODUCTION

While total greenhouse gas (GHG) emissions within the EU-27 could be reduced by more than 15% between 1990 and 2010, those from transport increased. With a share of 22%, road transport is the second biggest contributor of all sectors and the biggest in the transport sector (1). Technological progress in reducing fuel consumption of internal combustion engine (ICE) vehicles was not able to compensate for the ever increasing mobility demand until now. However, the European Union has committed to reducing its GHG emissions compared to 1990 levels by 20% by 2020 (1).

Since it is expected that GHG emissions from road transport will continue to increase if no measures are undertaken, it is important to assess the potential for reduction of different powertrain technologies (2). A widely discussed solution is the introduction of electric drivetrains in cars and light commercial vehicles. Several European governments such as Germany, the UK and France are pursuing this strategy (3; 4; 5).

Various studies have been conducted to predict future demand for such vehicles and to demonstrate potential GHG reductions (6; 7; 8; 9). However, the total emission reduction through EVs is dependent on the share of sources for energy production, which differs heavily within Europe (10). But besides the main motivation to reduce GHG emissions, EVs also provide a second advantage that is especially relevant for urban areas: the absence of local air pollutant emissions.

While customers generally give positive feedback about EVs and their performance or usability, important issues remain such as high cost, limited choice of models, limited range of BEVs and uncertainty about charging possibility and speed (6; 7; 9; 11; 12). Some of these parameters already started to evolve and major changes can be expected in the future (like cost reductions and model availability), others are key targets of new policies. It is therefore crucial to assess the total reduction potential, taking into account the main determining parameters such as taxes, fuel prices or the availability of governmental subsidies because all of them heavily influence the demand of such vehicles.

The research presented in this paper shows an approach for analyzing the German car market's potential for electric vehicles. The aim is to develop a methodology that allows calculating the impact of different scenarios on the potential for EV sales, fleet size and emission reduction. The instrument can provide valuable insights for policy design by assessing the possible market size under different circumstances. This paper distinguishes two concepts of EVs: Plug-in Hybrid EVs (PHEVs) and Battery EVs (BEVs), as their driving patterns and costs will differ significantly. Serial and parallel PHEVs concepts are not differentiated. Moreover, different ownership approaches are considered to illustrate how they influence the market potential. Technical, socio-demographic and economic limitations are modelled to derive possible sales potentials for electric passenger cars. The analysis covers the timeframe until 2030. Note that calculations are done in kilometres (km), where 1 km = 0.62 miles.

METHOD

Our model is based on a disaggregate processing of two National Travel Surveys. It combines information about current vehicle buying behavior of households and companies, available production volumes and current automobile sales per area with scenarios of technology development and customer behavior. The result is a geographic diffusion roadmap showing EV sales as well as fleet and mileage compositions for every German district in five-year steps. With this information, the reduction potential for greenhouse gases and air pollutant emissions can be calculated based on the replaced conventional car mileage. FIGURE 1 depicts the components of the model.

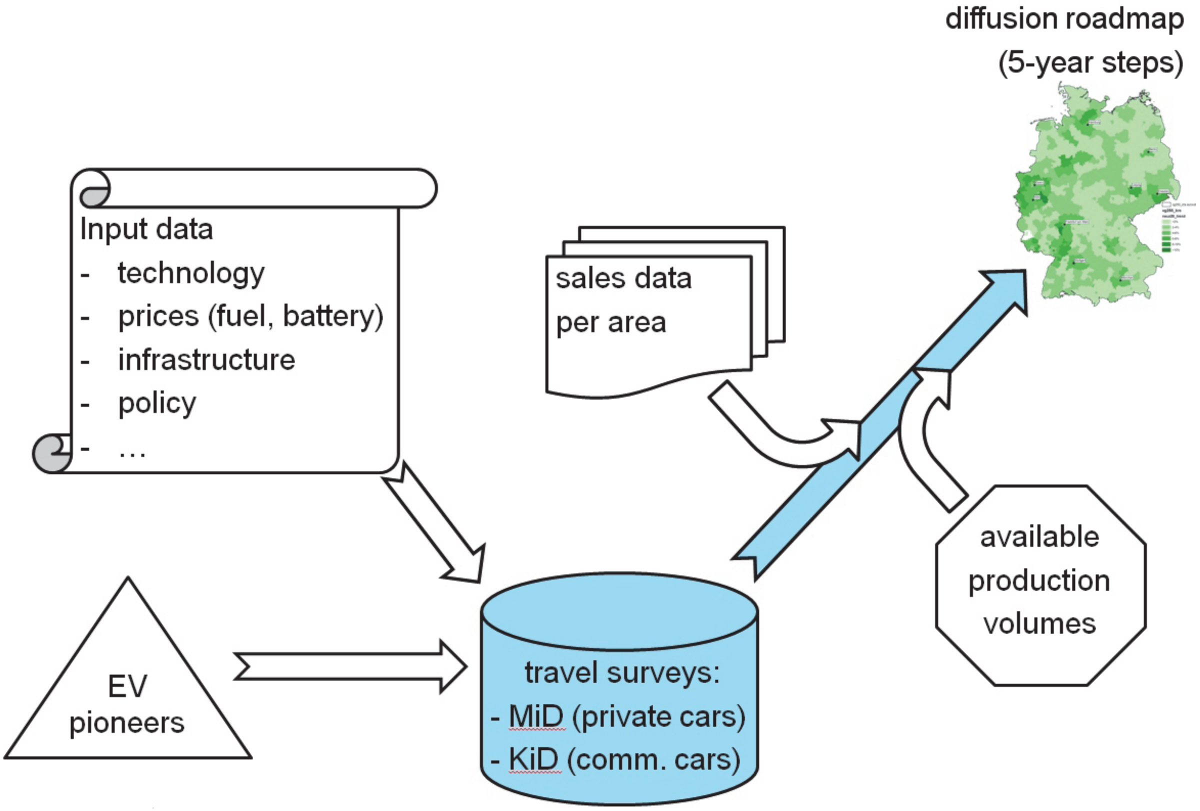

FIGURE 1 Model Components

The model simulates a respective buying situation in 2010 (to control for existing cars), 2015, 2020, 2025 and 2030 where PHEV or battery-electric BEV technology only impacts the drivetrain, not the whole vehicle's concept in itself. Vehicle purchasers in this model have a fixed preference for their current number, types and drivetrains of cars but are offered two alternative drivetrains (PHEV and BEV) within their desired segment. Our perspective on these alternatives can be best understood as extra features of the drivetrain, causing higher investment but lower cost per mile. The purchaser chooses an alternative if the net present value (NPV) of the investment is positive compared to its currently chosen conventional drivetrain. The NPV is calculated from the total annual cash flows C from period 0 (the date of the purchase) to period T (the last year of usage). It starts with the purchase price difference C_0, contains the annual savings C_t and ends with the resale price difference C_T:

$$\mathrm{C} = -\mathrm{C}_0 + \sum_{t=1}^{T} \mathrm{C}_t * (1+i)^{-t} + \mathrm{C}_T * (1+i)^{-T}$$

C_0 is the initial investment needed for the "upgrade" from the current drivetrain to the PHEV or BEV. It is calculated from the engine price difference Δp_{eng}, the battery size B, recharging equipment cost p_{ch}, a subsidy σ and an "eco-factor" ϵ allowing for some environmental attitude:

$$C_0 = \left(\Delta p_{eng} + p_{bat} * B + p_{ch}\right)^{1/(1+\epsilon)} - \sigma$$

We used battery price forecasts from the National Electromobility Development Plan (9) and variable battery sizes to reach a fixed defined range of 130 km (BEVs) and 30/40/50 km (small/medium/large PHEVs), respectively. The battery size is calculated for each period, depending on the assumed electrical energy consumption, which underlies a certain improvement over time. The prices for engine and recharging technology are used from [13]. The "eco-factor" is assumed to be 7%, based on willingness-to-pay estimates for green electricity (14). The subsidy is assumed to be zero, since the German government currently plans none.

C_t includes not only fuel cost, but also depreciation, maintenance, taxes and all other cost (and revenue) factors being potentially different between the drivetrain options:

$$C_t = m * \Delta c_m + \Delta c_a$$

with m being the annual mileage, Δc_m the difference in cost per mile and $\Delta c_a$the difference in annual cost. The parameter Δc_m itself consists of two elements:

$$\Delta c_m = \beta * \Delta p_f + \Delta p_w$$

where Δp_w denotes the difference in maintenance expenses due to lower wear coefficients of electric drives (see [13] and [15] for explanation and actual values), Δp_f the difference in fuel cost per mile and β the share of electric miles, which is 100% for BEVs but can be much lower in case of PHEVs with small batteries, depending itself on the annual mileage m. Assuming a uniform car usage on d days per year, we define the following:

$$\beta = \max(\frac{R * d * \gamma}{m}; \beta')$$

where R denotes the vehicle's electric range and the cap β' allows for an assumed minimum of combustion engine miles traveled anyway. γ is the so-called charge factor controlling for range-enhancing fast charge. This charge factor is the average charging power, calculated by the share s_i of each of the I recharging technologies and its power throughput P_i:

$$\gamma = \sum_{i=1}^{I} s_i * P_i$$

In our baseline scenario we assume a growth for three-phase charging of two percentage points per year, starting at zero in 2010. With no DC fast-charging rollout being assumed, γ therefore grows linearly from 1.0 in 2010 to 1.8 in 2030. The fuel cost difference Δp_f is the difference of the products of fuel consumption and price of the respective conventional fuel (index c) or electrical energy (index e):

$$\Delta p_f = p_c * c_c - p_e * c_e$$

Future energy prices are taken from the rather conservative fuel price of the official German traffic forecast "VP2025" (16), which for 2030 states 1.71 € per liter (around 8.5 $ per gallon at 1 € = 1.30 $), including all taxes. Values for energy consumption of conventional and electric vehicles are provided by the established German forecast model TREMOD [17].

Annual fixed cost differences Δc_a come from circulation (or other annual) taxes Δq and the savings/revenues from unidirectional and bidirectional vehicle-grid interaction, r_{V2G}.

$$\Delta c_a = \Delta q + r_{V2G}$$

While the former are easily calculated from the current regulation (no circulation taxes for BEVs and PHEVs, conventional cars tax based on engine size/type and GHG emissions and fringe-benefit tax for mixed-use company cars), the latter must be assumed. For the baseline scenario, we use a value of €2 per kWh of battery size, growing linearly to €10 in 2030.

In the case of leasing vehicles (which are not bought and resold by the user but paid for on a monthly base, partly depending on their actual mileage), Δc_a also contains the leasing cost differences Δl, which are calculated using the purchase price difference C_0, the leasing factor λ and the mileage billing parameters ω_1 and ω_2:

$$\Delta c_{a,leasing} = \Delta q + r_{V2G} + \Delta l$$

$$\Delta l = C_0 * (\lambda + \frac{\omega_1 - m}{\omega_2})$$

Based on own market research, we assume a leasing factor of 15.6% (monthly rates at 1.3% of the new car price) and mileage billing parameters of $\omega_1 = 20{,}000$ and $\omega_2 = 900{,}000$.

The resale price difference for non-leased vehicles C_T is calculated by a depreciation model for the EV equipment with a first-year depreciation δ_1, a subsequent annual depreciation δ_2, a mileage depreciation δ_3 and a cap at δ':

$$C_T = C_0 * (1 - \max((\delta_1 + \delta_2 * (T - 1) + \delta_3 * m); \delta'))$$

The first-year depreciation is assumed at 20%, followed by 5% for each subsequent year. The mileage-based depreciation is added on top and amounts to 4% per 10,000 km. The cap is set at 90% to account for the high material value of the new components (especially the battery). Note that the depreciation of the vehicle as a whole does not have to be calculated, the calculation relates only to the depreciation of the price difference between EVs and conventional cars.

Since electric drivetrains have high upfront investments and low marginal travel cost (15), the model calculates the minimum annual mileage needed to reach a positive NPV for both PHEVs and BEVs compared to both gasoline and diesel conventional drivetrains. Car buyers exceeding these minimum mileages are then assumed to choose the most cost-efficient option rationally. If PHEVs and BEVs are both competitive and their minimum annual mileages differ by less than 1,000 km, they randomly select one option.

This rational choice is relaxed for customers with a defined “EV pioneer” profile. Such customers are assumed not to care about the financial impacts of their choice but instead their social and environmental position. Based on various fleet tests with EVs (where participants had to apply and pay a monthly lease) as well as on literature review, we define this profile as follows (4; 18): Living in two-person households in large cities or their surroundings, having a high economic status and the main user of the car is male and between 30-60 years old. In case of company-owned vehicles, these companies are assumed to be located in large cities as well, have more than 1,000 employees and belong to certain business sectors (utilities, financial industry, real estate, services). While these “EV pioneers” are not numerous, they however explain well the (low, but already existing) demand for EVs in early periods where the cost is still very high.

Besides the economic requirements, potential customers also have to satisfy the following conditions to be able to acquire electric drivetrains:

- They must have bought a new car (i.e. no second-hand buyers).

- No reported trip was longer than the future electric range $R * \gamma$ (only for BEVs).
- Private customers must park the car for recharging in their own garage (or also somewhere else, depending on the infrastructure scenario).
- If a private household consists of two or more people, a BEV cannot be the only car in the household.

The results of the model have a resolution of two replaced drivetrains, four types of ownership (private, mixed-use company car, commercial fleet and LCV), ten vehicle categories and nine district types (from inner urban to remote rural). This resolution perfectly corresponds to the one of the current sales data per area to project the local sales volumes.

To estimate the fleet size from these sales volumes, we use survival rates and mileage decline from TREMOD (17) and assume a transition to the private second-hand market after three years for company cars and after five years for commercial fleet cars. With the information about each vehicles annual mileage and the calculated electric part of it, we can finally derive the fleet's total electric annual mileage, which replaces ICE mileage:

$$m_{replaced} = \sum_{\forall i, C(i) > 0} m_i * \beta_i$$

where $i, C(i) > 0$ denotes a vehicle i that is replaced because the EV investment $C(i)$ is profitable. These replaced conventional miles are the key result for straightforward air pollution calculations. It is possible to separate these results by the replaced drivetrain to use engine-specific pollutant coefficients.

DATA

We assumed constant sales figures and vehicle category distributions based on the sales data of the German KBA (Kraftfahrtbundesamt, Federal Motor Transport Authority) as of 01/01/2009. Since the 2009 sales data were subject to heavy changes from the scrapping premiums of the German stimulus package, the authors used the sales values of 2008 for modeling purposes. In total around 3.3 million cars and light duty vehicles were sold in 2008. Thereof 1.7M were registered on a company and around 1.4M were private registered vehicles.

We analyzed four different ownership segments according to their different usages and financing models: (1) private cars, (2) commercial fleet cars, (3) user-chooser company cars and (4) light-duty commercial trucks.

The data basis for the car fleet structure was derived from the two comprehensive studies MiD ("Mobiliät in Deutschland" 2008 (19)) for the private passenger cars and KiD ("Kraftfahrzeugverkehr in Deutschland" 2002 (20)) for company-owned cars. The key elements of these surveys are shown in TABLE 1.

TABLE 1 Characteristics of Datasets Used for Modeling

	KiD	MiD
Type of survey	National Travel survey	National Travel survey
Enquiry period	2001/2002	2008
Object of investigation	Vehicles	Households
Sample size	~77,000 vehicles	~26,000 households
Day-trips	~119,000	~193,000
Focus	Commercial transport	Private transport
Traffic modes investigated	Individual motorized traffic	Public and individual motorized and non-motorized traffic

MiD 2008 is the current successor of the “Continuous Survey on Travel Behaviour” (KONTIV) carried out in the former West Germany in 1976, 1982 and 1989 by the Ministry for Transport and the following MiD 2002. The main task of MiD is to compile representative and reliable information on the social demography of individuals and households and on their daily travel behaviour (e.g. trips made according to purpose and means of transportation used) for an entire year. Once it has been weighted and expanded, the information serves as a framework for and supplement to other travel surveys, such as traffic surveys in individual cities, cross-sectional censuses of traffic loads and the mobility panel. MiD also provides up-to-date data on important variables that influence mobility (e.g. number of driver's licences) and will be the basis for transport models. The results of the study are not only important for transport planning, research and academic interest; they also provide quantitative background information for concrete political decision-making.

KiD was conducted in 2001 and 2002 and put a focus on commercial vehicles that are registered by a company. By doing so, KiD 2002 is the first nationwide data available to access the characteristics and travel patterns of commercial motorized vehicles, including motorbikes, passenger cars as well as light commercial vehicles and heavy duty trucks. The questionnaire of KiD 2002, which mainly appears as a driver’s log, addresses the owner of a vehicle and records a one-day activity of the surveyed vessel, e.g. time of departure, destination and purpose of the trip. In addition to those data, detailed information from the KBA about every vehicle was added, e.g. kerb weight and fuel type. KiD 2002 comprises almost 77,000 vehicles and nearly 119,000 trips. That sample is representative of the whole German market in 2002. Thus KiD 2002 is a favorable source to analyze the market’s development towards electric mobility regarding commercial transport. For consistent modeling purposes, KiD 2002 data (readmissions and annual distance driven per vehicle) were recalculated to make sure that MiD and KiD are using the same starting point.

The sales data per area is provided by the KBA and contains the exact 2008 sales volume for each vehicle category and drivetrain for each of the 442 German districts. The production volumes we used in the model to control for the car manufacturers’ ability to produce the demanded quantity by 2020 are the result of extensive online and offline research.

RESULTS AND DISCUSSION

In the following chapter the results of the model will be described and discussed according to topics of interest. An overview of selected calculation results can be found in TABLE 2.

TABLE 2 Selected Results

Result	Segment	Technology	Veh. size	2015	2020	2025	2030
Sales (baseline)	CC	BEV	small	217	915	915	915
			medium	-	17,066	17,066	17,066
			large	2,999	10,429	10,429	11,037
		PHEV	small	612	51,252	68,501	77,020
			medium	713	713	389,916	408,525
			large	319	29,993	197,503	212,447
	LCV	BEV	small	13	51	98	187
			medium	41	3,121	13,350	27,817
			large	108	9,960	21,210	29,303
		PHEV	small	-	-	-	-
			medium	18	18	77	77
			large	22	22	1,643	1,728
	P	BEV	small	576	576	576	576
			medium	2,553	2,553	7,820	7,820
			large	3,537	3,537	3,537	3,537
		PHEV	small	332	332	77,325	121,467
			medium	2,381	2,381	123,353	263,722
			large	-	-	26,725	109,413
	CF	BEV	small	22	104	104	104
			medium	-	-	14,527	21,940
			large	-	246	4,093	4,093
		PHEV	small	163	163	52,547	75,186
			medium	-	-	-	76,294
			large	193	193	8,487	79,343
Fleet size (baseline)	all	BEV	all	31,521	189,578	527,214	967,627
		PHEV		14,057	272,621	3,190,682	8,701,557
Fleet size (baseline)	CC		all	11,639	266,709	1,701,337	2,144,063
	LCV			609	39,858	166,593	380,970
	P			32,213	152,824	1,612,744	6,232,231
	CF			1,118	2,808	237,222	911,920
Replaced M km/a (baseline)	all	petrol	all	624	7,087	36,111	77,043
		diesel		244	2,904	36,821	104,016
Fleet size (sensitivity: high fuel prices)	all	BEV	all	59,030	202,003	452,553	784,331
		PHEV		125,160	1,151,594	8,155,544	18,136,909
Replaced M km/a (sensitivity: infrastructure)	all	petrol	all	1,136	10,006	44,144	88,515
		diesel		319	9,093	53,958	128,047

Legend: CC = company cars, P = private cars, CF = commercial fleet cars

EV Sales Potential

The base scenario shows with over 130,000 electric vehicles sold per year in 2020 a slow increase of the EV sales potential starting in 2015 with a strong upward trend from 2020 until 2030 with around 1,550,000 vehicles already. Note that historically around 3.3M conventional cars and LCVs are sold per year in Germany. This translates that under the assumed conditions almost 50% of all cars sold in 2030 could be EVs. When we now implement the yearly sales figures into the vehicle stock we can see around 480,000 in 2020

EVs which account for around 8.5% of the total vehicle stock. With growing sales numbers between 2020 and 2030 the share of EVs in the vehicle stock rises to around a quarter of all registered cars.

The main influencing factor behind this development are of course high battery prices until 2020 which significantly reduce the profitability of EVs due to the resulting high upfront premium payment and limit the customers to early adopters and companies and private households with high annual mileage (for example, the minimum annual mileage for private households in 2025 is 23,500 km; in 2020, the value lies above our probability limit of 40,000 km). With dropping prices expected from 2020 on (3), EVs become more competitive with similar ICE vehicles and can be taken into consideration by drivers with an average annual mileage.

Although electric drivetrains are already more efficient than ICE drivetrains electric drivetrains are expected to still have a higher potential for efficiency increase which will reduce the average energy consumption per 100km e.g. for a medium sized vehicle from 23.8 to 19.6 kWh. In contrast, ICEs are expected to have lower efficiency gains due to their higher maturity. Please see (17) for detailed information.

Another limiting factor for an earlier market breakthrough of EVs is the lack of charging options especially for wide sections of private households. In Germany only around 70% of private registered vehicles have a garage available or park their vehicle on their own site to provide access to energy infrastructure for recharging an EV (19). Assuming that from 2015 on private drivers have the option of recharging their vehicle at the workplace, and from 2020 on also at shopping patterns including the option for fast charging, EVs become more profitable for a higher share of potential customers.

PHEV or BEV – Who is the Winner?

Within the first two periods of the observed timeframe PHEV registrations are significantly behind BEV registrations. While the absolute number of sold EVs in 2015 at around 15,000 vehicles is very low, only one third of these vehicles are PHEVs. The main reason for this result is the higher availability of BEV models in the market until 2015, which follows our market analysis of announcements and already available EVs by vehicle manufacturers. These limitations are expected to drop after the year 2015, which leads to fast-growing sales figures for PHEVs from 2015 onwards. Already in 2020, PHEVs sales are at around 85,000 vehicles almost twice as big as for BEVs. This development continues with PHEVs being the first choice for potential EV customers due to the higher profitability for the customer as well as non-existent limitations to use the vehicle as sole vehicle in the household. Compared to a BEV a PHEV can without restrictions be operated on longer trips e.g. for weekend trips or holidays with trip lengths over the real range $R * \gamma$. In our analysis we exclude the possibility that a private household owning only one vehicle will exchange it in favour of a BEV if it is reported in the MiD that this vehicle is also operated on longer journeys. This limitation falls with the year in 2025 when we assume a denser network of public fast charging points.

Customer Analysis

When analyzing the electrification of the different ownership types we can differentiate four stages. In the first stage until 2015 we see the highest demand in the private sector with around 32,000 registrations followed by user-chooser company cars. Pioneers drive the private as well as commercial registrations. Electric vehicles are not profitable until 2015 and only available in limited volume, which is specifically the case for PHEV.

From 2015-2020 EVs become profitable for private driver as well as user-chooser company cars given the vehicles will generate a high annual mileage. Therefore both segments grow. However, it can be observed that user-chooser company cars gain significantly higher shares due to the higher shares of vehicles with a high annual mileage. Besides these two segments LCVs also pick up and make up for around 40,000 registrations in the year 2020.

In the timeframe of 2020-2025 all ownership types gain increasing shares of EVs. Company fleet cars and LCVs are the fastest growing segment, coming from their low diffusion level to now catch up with the other segments. Registrations in the private sector make up already 1.6M in 2025 vehicles being the second largest sector. In the year 2025 the market for user-chooser company cars is almost saturated with 1.7M registrations.

Until 2030 we see the highest increase in relative and absolute numbers in the private sector. With ever decreasing prices for batteries, higher efficiency of drivetrains and availability of charging infrastructure EVs, the barriers for owning an EV become very low making it a profitable option even for vehicles with below-average annual mileages. The same is true for commercial fleet cars as well as LCVs. LCV with their often specific driving pattern and average daily mileage below 80km make up for the highest share of BEVs in 2030.

EV Size Distribution

There are several observations in the development of the PHEV and BEV potential: First, the competition between the two EV types is mainly decided by vehicle size – small electric vehicles are mostly BEVs while large ones are mostly PHEVs. One reason is that small vehicles in the household are less used for longer trips than medium or large vehicles and therefore can be replaced by a BEV with a restricted range. Furthermore smaller cars are often not the only vehicle in the household but rather a second or third vehicle. Therefore profitable medium or large sized EVs are expected only to be PHEV until 2020. With significantly decreasing battery prices from 2020 on the profitability of medium sized BEVs especially rises strongly and BEVs gain a share of 40% of potential EV sales in 2030. Regarding small vehicles, BEVs already dominate the market in 2025. Only large EV passenger cars are without exception PHEV due to comparatively high surcharges and longer trip patterns

Annual Mileages Replaced by EVs

It is of special interest to predict the total annual mileages that are replaced by EVs - this result is the direct input for straightforward emission calculation.

The replaced annual mileages grow proportionately with the fleet size of the respective segment. However, compared to the total fleet size the total mileage is dominated by company cars for a longer time since their annual mileage is generally higher.

We furthermore distinguished between the replaced fuel type (petrol or diesel) since most emission models use separate emission factors for them. While the additional investment in EVs compared to petrol cars is higher than to diesel cars, the savings per mile are also higher. The relation between replaced petrol and diesel miles therefore mainly depends on the relation of petrol and diesel prices. In our baseline scenario, we predict a strongly growing replacement of annual petrol kilometers from 624 million in 2015 to 77 billion in 2030. The replaced annual diesel kilometers take up lagged, at 244 million in 2015, but meet the petrol mileage replacement in 2025 (at 36 billion annual kilometers) to then surpass it and grow until 104 billion in 2030. Note that the total German demand for annual kilometers amounts to 647 billion kilometers (21). The potential for replacement is thus significant.

Regarding the vehicle sizes, the replaced mileages are mostly driven by large vehicles in the first periods while medium-sized ones grow increasingly and finally dominate in 2030. Logically, at this endpoint of our analysis these vehicles are mostly owned by private households.

Sensitivity Analysis: Gas Prices

The sensitivity analysis of the model on higher fuel prices demonstrates the potency of this lever. With around 1.35M registered EVs in 2020 already the potential fleet size triples and in 2030 almost 19M EVs are registered replacing almost 50% of the total vehicle fleet, doubling the potential compared to the baseline scenario described above.

When analyzing the customers of the vehicles it becomes clear that especially the sector of private buyers increases. Whereas in the scenario baseline most of the vehicles got into the private sector through the second hand market it is now profitable for many new car buyers to prefer an EV over an ICE-propelled car.

Besides the (expected) result that high fuel prices are the most important driver of the transition towards EVs, an interesting detail can be observed: While the PHEV fleet has largely increased, the number of BEVs is almost constant because the savings for PHEV miles compared to conventional vehicle miles outperform the BEVs higher investment for only slightly cheaper annual fuel cost.

Regional Analysis and Sensitivity to Charging Infrastructure

The highest sales potential in Germany until 2020 can be found in the metropolises and their suburban surroundings (see Figure 2). This is true for all scenarios and partly stems from the pioneers - but the main causes are shorter trips and more sales of the suitable vehicles categories in these areas.

For a sensitivity analysis, we defined an infrastructure scenario where widespread availability of recharging infrastructures is assumed. We translate this fact into a charge factor (γ, see above) which strongly grows to values of 1.6 in 2015, 3.2 in 2020, 4.1 in 2025 until 5.0 in 2030. This rather extreme assumption means that in 2030, drivers can actually drive a daily distance of five times their regular range due to fast charging. But for a sensitivity analysis, it delivers valuable insights about the effects of infrastructure on sales and usage potentials. The results can be found in Table 2 and Figure 2.

It can be observed that there is on average a higher share of EVs in sales. For example, in 2020, the general share increases by about 2% and in cities and suburban areas "gaps" were closed and EVs are now an option for more potential customers living in rural areas in the center of Germany as well as in western and southern part. This is mainly due to the possibility to overcome restrictions in maximum daily trip lengths that are supposedly higher in these areas. With a charging station at the workplace the savings through electric driving are significantly higher and a positive NPV can be achieved earlier.

The share of pure-electric BEVs is much higher in this scenario. While the 2020 PHEV fleet totals at 270,000 vehicles (which is less than in the baseline scenario), there are 330,000 BEVs – more than double the number of the baseline scenario. The explanation is straightforward: More recharging availability leads to a higher "real range" for the same investment – a fact of which BEVs benefit more than PHEVs. Note also that most of the inner city areas have a higher EV share in this scenario, which is mainly caused by the ability to recharge at work.

While the effect of such extreme infrastructure developments on EV shares can be seen as significant but rather limited, it has a high effect on the potential annual miles driven electrically, which rise by around 20%. The reason is twofold: While on the one hand BEVs become more competitive against PHEVs, more people are able to drive pure-electric cars. On the other hand, the PHEVs can be driven with a much higher electrical share.

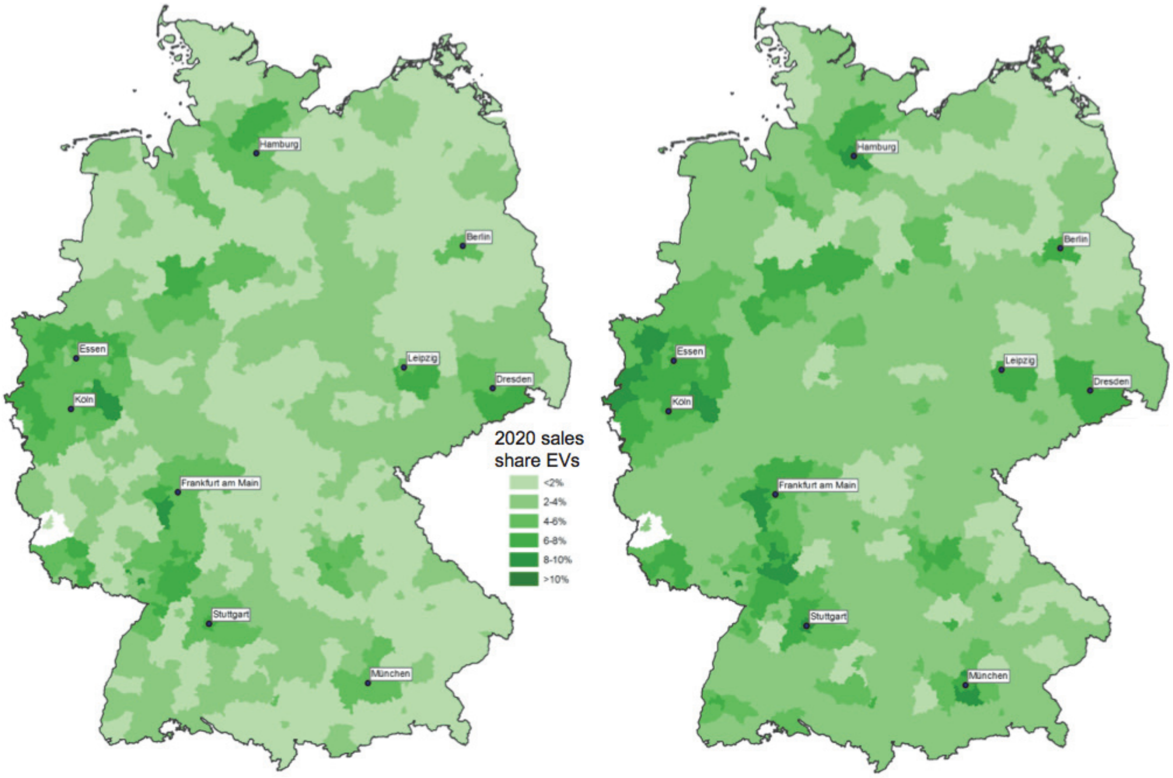

FIGURE 2: EV sales shares 2020 in the baseline (left) and in the infrastructure scenario

CONCLUSION

We defined a cost-oriented model of EV ownership to predict possible sales volumes, fleet sizes and driven mileages on a very disaggregate level of geographical area, ownership, vehicle size and replaced fuel type. The translation of mileages into emission savings is therefore straightforward, since most of this granularity can be used in detailed emission factors (which are often separate for petrol/diesel, urban/rural and small/large vehicles).

The results for Germany show a replacement potential of 180 billion annual vehicle kilometers in the baseline scenario, which is more than one fourth of the total German annual mileage of passenger cars and LCVs.

The main vehicle categories for potential replacement by EVs are large and medium-sized cars, of which many are first registered (and thus bought) by companies for mixed business-private use. After the leasing period (mostly three years), these vehicles quickly disperse into the private second-hand market, leading to a lagged but high share of private EV owners.

EVs replace both petrol and diesel cars, depending on the relation of these fuels' prices and the price difference of their engines. We estimated a larger petrol replacement first, followed by more diesel replacement after 2025.
While in the long run our model predicts PHEVs significantly dominating the EV market, BEVs can especially score in the LCV segment or in early periods if charging infrastructure is widely available.

High fuel prices have the expected strong impact on sales, fleet sizes and finally the replaced mileages. Logically, the relation is quite parallel to the relation between the fuel and energy prices in the scenarios.

The regional analysis shows the expected concentrations in urban areas but also clearly reveals that the potential of their respective surrounding suburbia is the largest market. Rural regions of very sparse EV potential strongly benefit from recharging infrastructure investments, as does the general share of electrically driven miles.

Future steps include the use of the calculated mileages to predict scenarios of air pollutant emissions for each district as well as the comparison of this drivetrain choice model to utility-based vehicle choice models.

The prediction of fleet sizes of electric vehicles in the future is an important task in order to demonstrate the possible impact of future developments concerning the transport sector such as increasing fuel prices but also to analyze the efficacy of measure that can help support the adoption of EVs and overcome the high investment costs e.g. by providing a higher profitability during vehicle operation through the deployment of a public charging infrastructure. The results can provide valuable insights for policy design as well as for transport and environmental modeling at the same time.

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