33rd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Future regional distribution of electric vehicles in Germany

Daniel Speth[1*], Till Gnann[1], Patrick Plötz[1], Martin Wietschel[1,2], Jan George[1]

[1]*Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139 Karlsruhe, Germany*

[2]*Institute for Industrial Production (IIP) at the Karlsruhe Institute of Technology (KIT),*

Hertzstrasse 16, 76187 Karlsruhe, Germany

**daniel.speth@isi.fraunhofer.de*

Summary

Electrification as an option to decarbonize road transport leads to an increasing number of electric vehicles in Germany. However, the stock of electric vehicles is not evenly distributed regionally. The local distribution of electric vehicles is particularly important from an energy system perspective in order to be able to estimate future grid loads. Here, we use multiple linear regression to distribute a German-wide market diffusion of electric vehicles to 401 NUTS3-areas in Germany. Current regional vehicle stocks and regional development data (e.g. population, income, and spatial structure) are used as independent variables. We combine these variables with forecasts for spatial development and obtain a regionalized electric vehicle market diffusion for Germany. First results suggest a concentration of BEV and PHEV stocks in southwestern Germany and in large cities in the medium-term future.

Keywords: electric vehicle (EV), fleet, market development, modeling, user behaviour

1 Motivation

Currently, electric vehicles are discussed as an opportunity to decarbonize the transport sector, which is responsible for about 20 % of CO_2 emissions in Germany [1]. In the passenger car sector, a growing number of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) is commercially available.

From an energy system perspective, the local integration of electric vehicles plays a decisive role with respect to additional energy demand or the usage of electric vehicles as local energy storage. Local electricity demand is also important for further installation of power plants and grids. Therefore, the future regional distribution of electric vehicles is of particular interest.

In this paper, we demonstrate an approach to regionalize the market diffusion of electric vehicles in Germany until 2050. As drivetrains, we take BEV and PHEV into account.

2 Methods and Data

Our approach consists of two major steps. In the first step, we generate a German-wide market diffusion of electric vehicles. In a second step, we distribute the future annual registrations to 401 NUTS3-areas[1] using multiple linear regression. For each region, the local registrations will be summed up by a simple stock model.

Step 1: Simulation of market diffusion

We use the ALADIN model (ALternative Automobiles Diffusion and INfrastructure), an agent-based simulation tool of alternative fuel vehicles purchase decision, to generate a market diffusion scenario for electric vehicles in Germany. The model uses real-world driving data from several thousand vehicles to determine the utility maximizing drive train option for each buyer. Based on a total cost of ownership (TCO) approach ALADIN also takes into account various constraints, such as infrastructure availability, but also supportive factors such as a willingness to pay more of some buyers. For further details regarding the ALADIN model, see also www.aladin-model.eu. With regard to the underlying parameters, we focus on the long-term scenarios of the German Federal Ministry for Economic Affairs and Energy [2].

Step 2: Regional distribution

The distribution of given Germany-wide registrations follows a three-step procedure.

First, we use multiple linear regression to explain historic BEV and PHEV sales shares in regions of Germany (dependent variables). BEV and PHEV sales shares are regressed on various explanatory variables separately. The Federal Motor Transport Authority provides sales of BEV and PHEV on NUTS3 level for 2017 and 2018 [3,4]. We assume local electric vehicle sales to be dependent on population and area. There are more car sales in highly populated, large areas than in small areas with less inhabitants. Studies show that BEV and PHEV are typically bought by persons with higher incomes [5]. Accordingly, we include local GDP and Employment as variables. Finally, car manufacturers register high number of vehicles themselves, either as vehicles for their car sharing subsidies or as company cars. Therefore, we include car manufacturer locations and their headquarters as dummy variables. The full regression model is given in equation (1). We use ordinary least squares to estimate the regression coefficients.

$$\log\left(\frac{Reg_{r,t,s}}{\sum_r Reg_{r,t,s}}\right) = \beta_1 \log\left(\frac{Pop_{r,t}}{\sum_r Pop_{r,t}}\right) + \beta_2 \log(Area_r) + \beta_3 \log\left(\frac{GDP_{r,t}}{\sum_r GDP_{r,t}}\right) + \beta_4 \log\left(\frac{Emp_{r,t}}{\sum_r Emp_{r,t}}\right) + \beta_5\, CarI_r + \beta_6\, CarH_r + \alpha \quad (1)$$

$Reg_{r,t,s}$	Annual registrations in region *r* in year *t* of drivetrain *s* [#]
$Pop_{r,t}$	Population of region *r* in year *t* [#]
$Area_r$	Area of region *r* [km^2]
$GDP_{r,t}$	Gross domestic product of region *r* in year *t* [EUR]
$Emp_{r,t}$	Employees in region *r* in year *t* [#]
$CarI_r$	Bivariate variable indicating car industry in region *r*
$CarH_r$	Bivariate variable indicating car industry headquarter in region *r*

The described procedure is particularly suitable in an early market stage in which mainly innovators and early adopter buy electric vehicles. During further market diffusion, we assume falling prices, an increasing variety of models and thus sales growth for electric vehicles. An electric drivetrain gradually becomes the standard vehicle drivetrain. We assume that purchasing behavior will also increasingly correspond to that of a conventional vehicle. Therefore, we calculate a third regression using all vehicle sales shares as dependent variable. To assess the accuracy of the regressions we compute root mean squared errors (RMSE), mean absolute percentage error (MAPE) and R^2_{adj} according to equation (2), (3) and (4).

[1] Nomenclature of Territorial Units for Statistics, Level 3: Counties and independent cities

$$RMSE = \sqrt{\frac{1}{N}\sum_i (y_i - \hat{y}_i)^2} \quad (2)$$

$$MAPE = \frac{100\ \%}{N}\sum_i \left|\frac{y_i - \hat{y}_i}{y_i}\right| \quad (3)$$

$$R_{adj}^2 = 1 - (1 - R^2) * \frac{N-1}{N-P-1}\ with\ R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y}_i)^2} \quad (4)$$

N	Sample size
K	Number of independent regressors
y_i	Observed value
$\hat{y}_i$	Estimated value

Second, we forecast future regional shares on German-wide BEV- and PHEV-registrations for all 401 regions until 2050 using the calculated regression coefficients and forecasts for the individual variables from spatial development studies [6]. Using weights, we converge from the regression for BEV or PHEV today into the future long-term regression of all vehicles. The calculations for 2018 completely follow the regression for BEV or PHEV. The calculations for 2050 are based on the regression for all vehicles. Equation (5) illustrates this relationship[2].

$$share_{r,t,s,final} = \left(1 - \frac{1}{32} * (t - 2018)\right) * share_{r,t,s} + \left(\frac{1}{32} * (t - 2018)\right) * share_{r,t,all} \quad (5)$$

$share_{r,t,s,final}$	Final share of vehicle registrations with drivetrain *s* in region *r* in year *t* ∈ [2018;2050]
$share_{r,t,s}$	Share of predicted vehicle registrations in region *r* in year *t* according to regression for drivetrain *s*
$share_{r,t,all}$	Share of predicted vehicle registrations in region *r* in year *t* according to regression for all vehicles

Third, we use annual electric vehicle registrations from step 1 and the calculated regional registration shares to estimate the absolute number of registrations per region. For every region, a regional stock model sums up the annual sales for BEV and PHEV.

3 Results and discussion

Regression results

Table 1 sums up the coefficients of the three regression models. The table shows the coefficient estimates β_i as well as the standardized coefficients b_i to compare the influence of the different independent variables. A variable is standardised by subtracting its mean from each of its values and then dividing by the standard deviation of the variable.

In all regressions, a high GDP share and a high employees share, i.e. a high share of all workers in Germany work in the given region, have a positive effect on the registrations in the considered county or city. This seems reasonable, as purchasing power is higher in economically strong regions. At first glance, the negative influence of a population share for BEV and PHEV is surprising. One possible reason is the low spread of electric vehicles today. Residents in surrounding areas seem to buy electric vehicles proportionally more often than residents in densely populated areas. The higher investment for an electric vehicle could be

[2] Due to small deviations, the sum of final shares of vehicle registrations within a year has to be normalized to unity afterwards.

compensated by higher mileage due to lower variable costs. Moreover, it is easier to install private charging infrastructure when having an own parking lot. Therefore, penetration in rural areas at an early market stage seems realistic. However, this possible connection should be examined in the future when electric vehicles have higher market shares. In our regressions, locations of the car industry have a negative influence on the registrations of electric vehicles, but a positive influence on vehicle registrations in general. This may be due to the higher import rate for electric vehicles in comparison to conventional vehicles. A manufacturer headquarter has a positive influence on the share of registered vehicles in the area in all regressions. This may include company cars and sharing vehicles registered at the headquarter location.

Table 1: Regression coefficients β_i and standardized regression coefficients b_i

	BEV			PHEV			All vehicles		
	β_i	b_i		β_i	b_i		β_i	b_i	
intercept	-0.042			2.162		***	0.065		
(log of) population share	-4.107	-2.916	***	-2.591	-1.749	***	0.237	0.196	
(log of) area	0.039	0.045	.	-0.105	-0.117	***	-0.052	-0.071	**
(log of) GDP share	0.365	0.299	***	0.249	0.193	*	0.533	0.507	***
(log of) employees share	4.789	3.424	***	3.604	2.452	***	0.213	0.177	
car industry	-0.348	-0.111	***	-0.233	-0.069	*	0.120	0.045	*
car headquarter	0.692	0.097	***	0.053	0.006		1.083	0.177	***

Signif. codes: "***" $p < 0.001$; "**" $p < 0.01$; "*" $p < 0.05$; ".": $p < 0.1$

Table 2 contains the accuracy measures for all three regressions. While the figures in brackets refer to the logarithmic shares used in the regression, estimated and actual shares serve as input for the figures without brackets.

Table 2: Accuracy measures for all three regressions. Figures in brackets refer to logarithmic regional shares.

	RMSE	MAPE	R^2_{adj}
BEV	0.0023	42.939	
	(0.498)	(5.919)	(0.714)
PHEV	0.0025	43.532	
	(0.486)	(5.781)	(0.754)
All vehicles	0.0026	18.876	
	(0.285)	(3.206)	(0.872)

Figure 1 compares actually observed and predicted shares of registrations for BEV and PHEV in 401 NUTS3-areas in 2017[3] and 2018. As already indicated by the accuracy measures, there are several outliers due to the

[3] No data available for PHEV in 2017

early market stage. Either these outliers are rural regions with a very low share of electric vehicles or cities with a car manufacturer headquarter. In the first case, the model overestimates electric vehicle registrations. In particular, in small municipalities the penetration of electric vehicles depends on charging infrastructure, which is available in strongly varying degrees today. In the second case, different attitudes of car manufacturers towards electric vehicles could be an explanation. In comparison to BEV and PHEV, the deviation of all vehicle registrations (Figure 2) is much smaller.

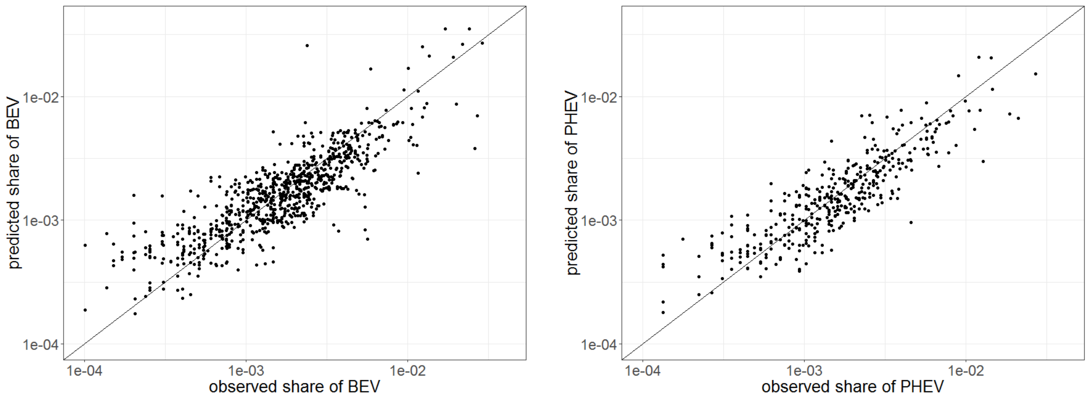

Figure 1: Comparison of predicted and observed regional shares on German-wide BEV- and PHEV-registrations

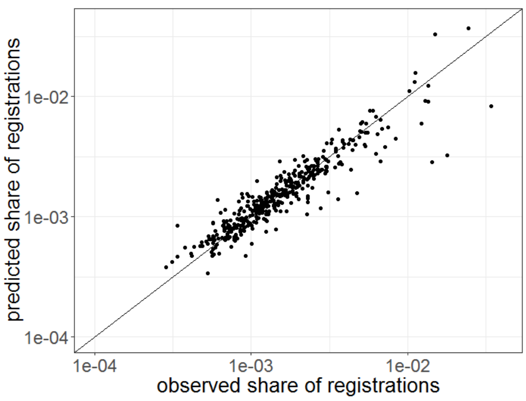

Figure 2: Comparison of predicated and observed regional share on German-wide vehicle registrations

Market diffusion

The first result represents the assumed German-wide market diffusion. The scenario expects an increase in the number of registrations of alternative fuel vehicles, dominated by BEV and PHEV. Gas-powered vehicles (CNG) and fuel cell vehicles (FCEV) are of minor interest in this scenario.

Figure 4 shows the obtained regional distribution of BEV and PHEV passenger cars in 2030 and 2050 from the combination of the German wide market diffusion and the regional distribution according to the linear regression model. In 2030, the electric vehicle stock in densely populated south and western areas of Germany is much higher than in less populated areas in eastern Germany. In 2050, the difference has been reduced, but is still noticeable. Higher purchasing power and higher population are the main reasons for the higher stock of EV in the darker areas. In general, comparably high BEV and PHEV stocks are in congested urban areas like Berlin, Hamburg, Stuttgart or Munich. Typically, these areas are automotive industry locations too, which further increases vehicle stock. In 2050, the highest stock of electric vehicles (1,391,000 BEV and 969,000 PHEV) is registered in Munich. However, it can be assumed that these vehicles include sharing vehicles and company cars used all over Germany.

Figure 5 shows the local share of BEV and PHEV in the local fleet in 2030 and 2050.

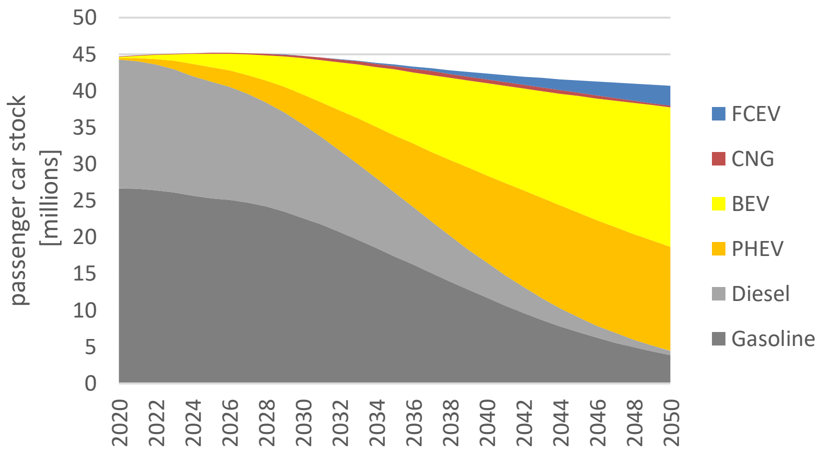

Figure 3: German-wide market diffusion scenario of BEV and PHEV passenger cars

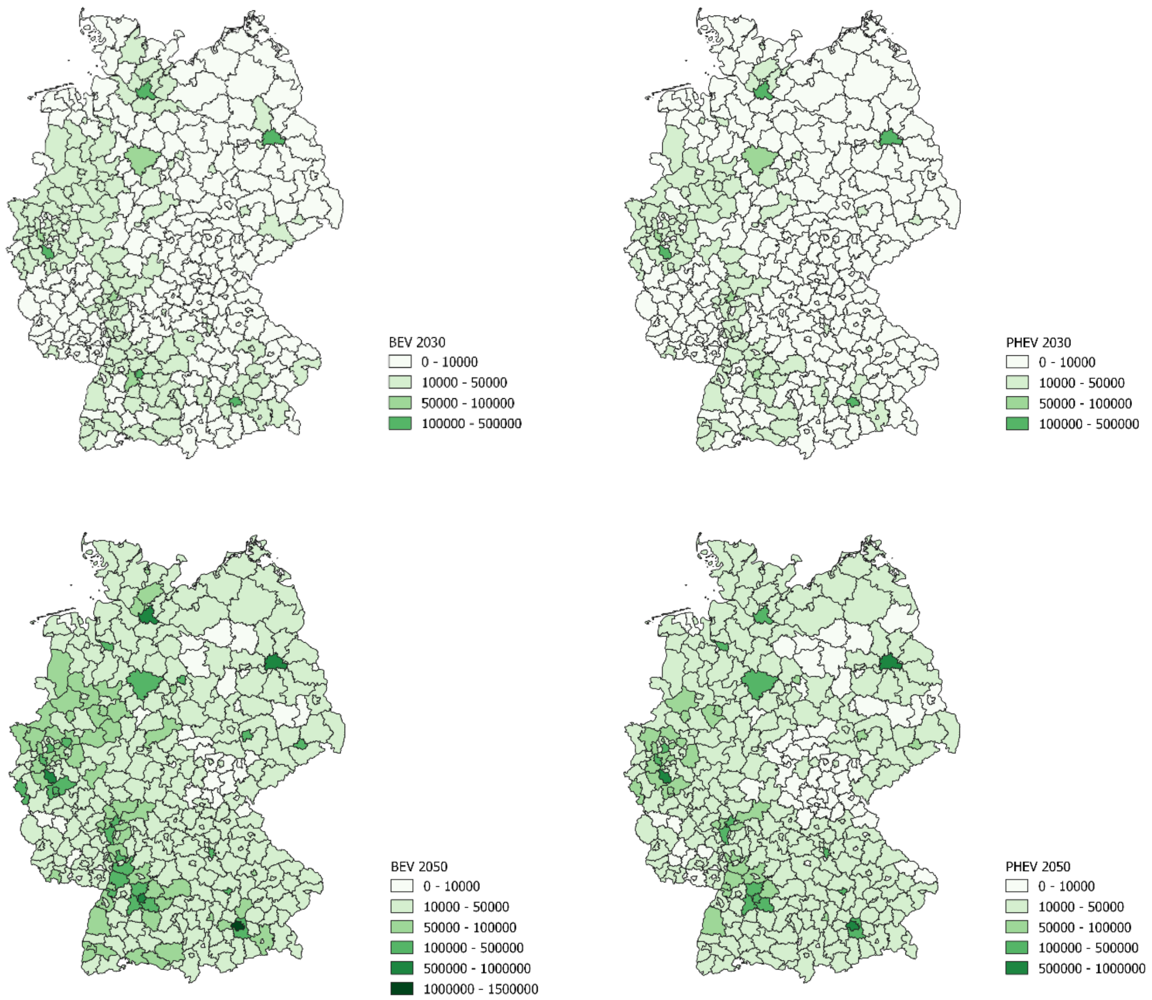

Figure 4: Spatial distribution of passenger BEV (left panel) and PHEV (right panel) stock in 2030 (top row) and 2050 (bottom row)

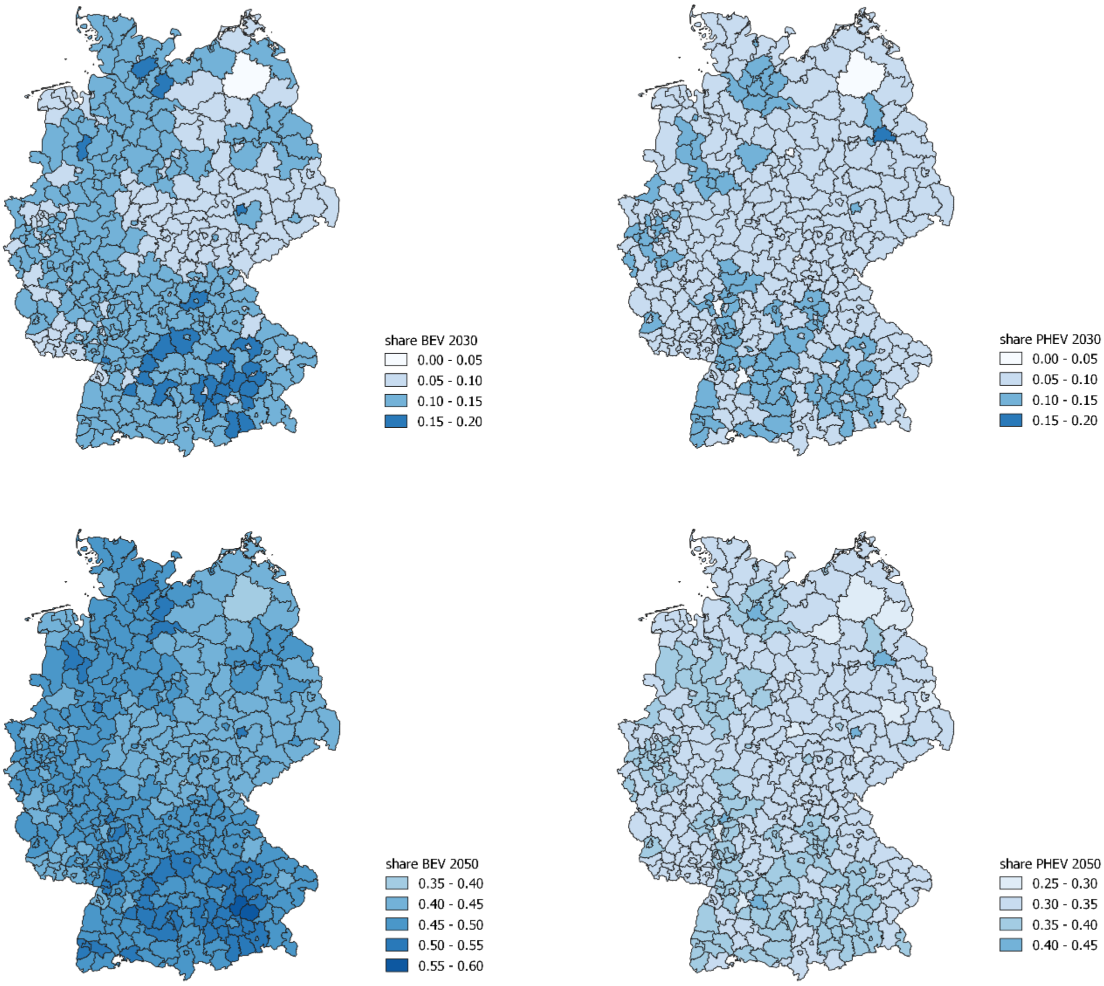

Figure 5: Electric vehicles stock share in a given region in percent for BEV (left panel) and PHEV (right panel) in 2030 (top row) and 2050 (bottom row).

Discussion

This paper attempts to estimate the future distribution of electric vehicles in Germany. Our results show that multiple linear regression is a valid option to develop a regional electric vehicle diffusion scenario. Due to the early stage of market diffusion for BEV and PHEV, the approach is still confronted with several uncertainties. The described time-dependent transfer to the regression for all vehicles is a first attempt to deal with this topic. However, the distribution should be evaluated within the next years in order to improve the regression accuracy by a larger dataset.

Our regression model comes with some uncertainty. First, the independent variables show some weak correlation and future studies should attempt to remove effects of collinearity. Second, we did not perform a full model selection or include interaction effects and future studies could identify combinations of predictors with higher explanatory power. Yet, for the present task of predicting future regional sales distribution of EV in a simple fashion that can be easily incorporated in a market diffusion, we believe that our model captures the dominant effects.

Acknowledgments

The authors would like to acknowledge the project Profilregion Mobilitätssysteme Karlsruhe, which is funded by the Ministry of Economic Affairs, Labour and Housing in Baden-Württemberg and as a national High Performance Center by the Fraunhofer-Gesellschaft. Parts of the analysis were supported by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the project MethSys (FKZ 03EIV046).

References

[1] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, *Klimaschutz in Zahlen (2018) – Fakten, Trends und Impulse deutscher Klimapolitik,* Berlin 2018.

[2] Federal Ministry for Economic Affairs and Energy, *Langfrist- und Klimaszenarien,* https://www.bmwi.de/Redaktion/DE/Artikel/Energie/langfrist-und-klimaszenarien.html [accessed: 17.03.2020].

[3] Federal Motor Transport Authority, *Fahrzeugzulassungen (FZ). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken: FZ 1,* Flensburg 2017-2019.

[4] Federal Motor Transport Authority, *Fahrzeugzulassungen (FZ). Neuzulassungen, Besitzumschreibungen, Außerbetriebsetzungen von Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken: FZ 5,* Flensburg 2018-2019.

[5] Plötz P., Schneider U., Globisch J., Dütschke E., *Who will buy electric vehicles? Identifying early adopters in Germany,* „Transportation Research Part A: Policy and Practice“ 2014 (67), p. 96–109.

[6] Federal Institute for Research on Building, Urban Affairs and Spatial Development, *Raumordnungsprognose 2035 nach dem Zensus 2019* 2019.

Authors

Daniel Speth studied Industrial Engineering and Management at the Karlsruhe Institute of Technology (KIT). His master thesis dealt with European CO_2-legislation for passenger cars and its implications on market ramp-up of alternative fuel vehicles. Since 2019, he is a researcher at the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovation research in Karlsruhe, Germany. Areas of work are the modelling of market diffusion for electric vehicles with a special focus on heavy-duty vehicles and its implications on the energy system.

Dr. Till Gnann studied industrial engineering at the Karlsruhe Institute of Technology (KIT) (formerly University of Karlsruhe) and at the Politecnico di Milano (Italy). He gained overseas experience in Santa Clara, CA (USA). His diploma thesis examined the „technical and economic assessment of preconditioning electric vehicles“ at the Fraunhofer Institute for Systems and Innovation Research ISI. Since April 2011 he has been working in the Competence Center Energy Technology and Energy Systems. He received his PhD from the Karlsruhe Institute of Technology (KIT) in 2015 on „Market diffusion of plug-in electric vehicles and their charging infrastructure”.

Dr. Patrick Plötz studied Physics in Greifswald, St. Petersburg and Göttingen. Dissertation in Theoretical Physics on correlated electrons in one-dimensional systems. Additional studies of Philosophy and History of Science in Göttingen. Doctorate degree in Theoretical Physics from the University of Heidelberg (Institute for Theoretical Physics) on complex dynamics in cold atomic gases. From January to December 2011 researcher in the Competence Center Energy Policy and Energy Systems at the Fraunhofer Institute for Systems and Innovation Research ISI, since January 2012 in the Competence Center Energy Technology and Energy Systems.

Prof. Dr. Martin Wietschel studied Industrial Engineering and Management at the University of Karlsruhe. From 2002 to 2011 member of the Competence Center Energy Policy and Energy Systems at the Fraunhofer Institute for Systems and Innovation Research ISI, since January 2012 Deputy Head of the Competence Center Energy Technology and Energy Systems. Since 2007 Coordinator of the Business Unit Energy Economy. From 2005 to 2011 lecturer at the ETH Zurich and since 2008 adjunct professor at the University of Karlsruhe (now Karlsruhe Institute of Technology (KIT)).

Jan George studied industrial engineering at the Technical University of Clausthal (TUC) and at the University Polètecnica of València. He graduated with a Master's degree with specialisation in Management of Energy and Raw Materials. Through a large number of industrial internships and working student activities as well as an employment as a management consultant, he helped to shape energy-industry projects and supported research and teaching for several semesters as a research assistant at the Chair of Accounting at the Institute of Economics of the TUC.