# Electric Vehicle Market Penetration and Corresponding $CO_2$ Emissions: A German Case Study for 2030

**Patrick JOCHEM*, Sonja BABROWSKI, Wolf FICHTNER**
* Karlsruhe Institute of Technology (KIT), Institute for Industrial Production (IIP), Chair of Energy Economics
Hertzstr. 16, Building 06.33, D-76187 Karlsruhe, Germany
Tel.: +49 721 608-44590, Fax: +49 721 608-44682, E-Mail: jochem@kit.edu

## (1) Overview

The European Regulation No 443/2009 puts high pressure on the future market for passenger cars in Europe. The average target of 95 gr. of $CO_2$ emissions per km in 2020 for the new registrations is challenging and seems to be hardly achievable with business as usual measures. Electric vehicles (EV) are said to be an efficient technology to reduce $CO_2$ emissions. This hypothesis is strongly connected to the uncertainties of the market penetration of EV and the underlying actual energy mix of electricity generation during the charging process. Therefore, we first simulate the individual German road transport sector until 2030 with regard to the annual mileage of the vehicles with the meso-economic multi agent based model COMIT. We substantially updated the integrated vehicle demand module of COMIT and strengthened the technology decision approach. We developed two scenarios in order to take the high uncertainty about the vehicles purchase decision in the future into account. Then, using the calculated market penetration of 1.43 million (6 million) EV in 2030, we identify the mix of electricity to satisfy the corresponding additional electricity demand of 2.12 TWh (8.5 TWh) in consideration of the charging time (instantaneous charging). Furthermore, we use the cost optimizing energy system model PERSEUS-NET to compare the resulting electricity mix and the $CO_2$ emissions of the energy sector with and without EV.

The hypothesis that EV are an efficient technology to reduce greenhouse gases is mainly based on two uncertainties: (1) The market penetration is unclear and (2) the specific emission reductions do highly depend on the underlying actual energy mix of electricity generation during the charging process. Therefore, we focus on the market penetration by the COMIT model and on the electricity mix by the PERSEUS model.

## (2) Methods

Due to the heterogeneous and sometimes spontaneous decisions of households in the transport sector, multi-agent models represent a suitable alternative of simulating road passenger transport (see Jochem, 2009). The model includes the vehicle purchase decision with different drive chain technologies (gasoline, diesel, natural gas, autogas, plug-in electric vehicles (PHEV) and battery electric vehicles (BEV)) based on social aspects of the household (e.g. education) and the household specific costs according a comprehensive TCO analysis of each vehicle available. Furthermore, it includes the $CO_2$ emissions during the driving cycle.

The COMIT ($CO_2$ emission MItigation in the Transport sector) model includes 700 different households and more than 600 different road freight transport actors, which represent the German traffic participants and is based on empirical data (German Mobility Panel, 2011). The main agents are households (demanding fuel and new passenger cars), vehicle manufacturers (providing new cars), and oil companies (importing/refining and selling fuel). The updated vehicle demand module includes the following decision path:

The households decide once a year whether to buy a new (or used) car or continue to drive their old one. If they decide to buy a car, a two stage decision is accomplished (cf. Mueller and de Haan, 2009, or Mock et al., 2009). First, the age of the vehicle is estimated according to a logit model by Jochem (2009), before the vehicle segment is chosen in the second step based on the segment of the old vehicle and certain probabilities of segment changing. For each segment a synthetic sample of vehicles is deposited in a database. For some households (which (a) do not have the possibility to use a private parking lot and / or (b) undertake trips longer than the range of electric vehicles) the electric alternative is rejected. Second, in order to choose a particular vehicle out of the selected segment, for each sample vehicle the corresponding utility is calculated according a twofold utility function ($U_{i,k}^{\Sigma}$) given in equation 1. The utility function consists of social valuations ($U_{i,k}^{soc}$) and cost estimates ($U_{i,k}^{TCO}$), based on TCO analysis. Both terms are dependent on the parameters of the households ($i$) and vehicles ($k$). Obviously, the vehicle with the highest utility is chosen by the household.

$$U_{i,k}^{\Sigma} = \alpha^{soc} \cdot \overline{U}_{i,k}^{soc} + \alpha^{TCO} \cdot \overline{U}_{i,k}^{TCO} \tag{1}$$

$$\text{with } \overline{U}_{i,k}^{soc} = \frac{1}{1+e^{-\beta_k \cdot x_{i,k}}} \text{ and } \overline{U}_{i,k}^{TCO} = \frac{U_{i,k}^{TCO}}{\max\limits_k \left(U_{i,k}^{TCO}\right)} = \frac{\dfrac{ep_k}{C_k^{fix} + C_{i,k}^{\text{var}}}}{\max\limits_k \left(\dfrac{ep_k}{C_k^{fix} + C_{i,k}^{\text{var}}}\right)} \qquad \text{(2a) and (2b)}$$

In our basic scenario both terms are equally weighted (i.e. $\alpha^{soc}$ = 1 and $\alpha^{TCO}$ = 1). The household specific social valuation ($\overline{U}_{i,k}^{soc}$) is represented by the logit model by Achtnicht (2012) and its parameters ($\beta_k$) and variables ($x_{i,k}$)

(eq. 2a). The cost based utility ($\overline{U}_{i,k}^{TCO}$) (c.f. Jochem et al., 2012) is dependent on the energy performance of the vehicle engine ($ep_k$) and the net present value of the annual fixed costs ($C_k^{fix}$) and household specific variable costs ($C_{i,k}^{\mathrm{var}}$) of the vehicle and is normalised to the interval {0,1} (eq. 2b).

The optimizing energy system model PERSEUS-NET (Eßer-Frey, 2012) is a bottom-up model representing the German energy system and belongs to the PERSEUS family (Rosen, 2007). The model is written in GAMS and is based on a linear optimization and consists of over 3 million equations and variables. With a time frame until 2030 PERSEUS-NET calculates the redevelopment plans for coal, lignite and gas power plants throughout Germany. The driving force is the exogenously given demand, which has to be satisfied while minimizing the global costs of each period. Those costs are composed of fuel supply and transport costs, fixed and variable costs of the power plants, load variation costs and investments in new power stations. In PERSEUS-NET 440 administrative districts (Kreise) are modeled with their specific power plants and demand. The model balances for each Kreis the material and energy flows for each hour of one representative summer and one representative winter week. These balancing equations are complemented by equations restricting the use of the power stations according to their technological characteristics and equations depicting a DC approach of the German transmission grid.

The development of renewable energy supply (RES) in each county is given. This is due to the fact that they are neither constructed based on economic reasons alone nor because of a strategically good position in terms of the demand, but rather because of regulations, politics, and regional potentials. Thus based on a 30 % share of RES in electricity generation in 2030, the distribution of generating capacity is calculated considering regional potentials (Eßer-Frey, 2012). The RES feed-in is based on historical data representing its characteristic course. For the following calculation, the model was slightly adjusted by replacing the perfect foresight approach by a myopic approach. The results indicate the underlying hourly electricity mix for 1.43 (6) million additional EV in 2030 for a summer and a winter week and the corresponding $CO_2$ emissions.

## (3) Results

The resulting share on EV on the fleet is 2 % for rural and semi-rural areas, 3 % for cities and 7 % for the commuter belts surrounding big cities. The average mileage per day is similar to the overall average and ranges for these early adopters from 33.7 km (cities), 36.8 km (semi rural), 37.3 (commuter belts surrounding big cities) to 38.2 km (rural areas). A sensitivity analysis for the car purchase decision illustrates the main parameters for influencing the EV penetration. The electricity consumption by EV (mostly PHEV with 91 %) for each county serves as input for the energy system model PERSEUS in order to calculate the impact on the German energy system. According to PERSEUS-NET, this additional demand leads to a marginal investment in additional fossil power plant capacities with correspondingly increasing $CO_2$ emissions. The $CO_2$ emissions for the charging process differ considerably with respect to winter and summer terms as well as over time (depending on the current share on RES).

## (4) Conclusions

The vehicle demand module depicts only low shares of EV, which seems to help only marginally in mitigating $CO_2$ emissions in the German road passenger transport. The impact on overall emissions, however, depend strongly on the volatile electricity generation by RES and therefore on the scheduling of EV charging. Hence, a postponed charging of EV could have a considerable impact on the $CO_2$ emission reduction potential by EV.

## References

Achtnicht, M. (2012), German car buyers' willingness to pay to reduce $CO_2$ emissions, *Climatic Change* 113(3), 679-697.

Eßer-Frey, A. (2012), *Analyzing the regional long-term development of the German power system using a nodal pricing approach*, Dissertation, Karlsruhe.

German Mobility Panel (2012), data from http://www.mobilitaetspanel.de

Jochem, P. (2009), *A $CO_2$ Emission Trading Scheme for German Road Transport – assessing the impacts using a meso economic model with multi-agent attributes*, Dissertation, Baden-Baden.

Jochem, P., S. Babrowski, and W. Fichtner (2012), *$CO_2$ emission reduction potential of electric vehicle and their impact on the transmission grid in Germany*, presentation at the OR conference 2012, Hannover.

Mock, P., D. Hülsebusch, J. Ungethüm, and S.A. Schmid (2009), Electric Vehicles – a Model Based Assessment of Future Market Prospects and Environmental Impacts, *EVS24 conference proceedings*, Norway

Mueller, M., and P. de Haan, (2009), How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars – Part I: Model structure, simulation of bounded rationality, and model validation, *Energy Policy* 37, 1072-1082.

Rosen, J. (2007), *The future role of renewable energy sources in European electricity supply: A model-based analysis for the EU-15*, Dissertation, Karlsruhe.